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Properties of Prealloyed Steel Powder Metallurgy Products

Battelle Memorial Institute

prepared for
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PROPERTIES OF PREALLOYED STEEL POWDER METALLURGY PRODUCTS

- FINAL REPORT -

TECHNICAL REPORT

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DECEMBER 1972

RESEARCH DIRECTORATE

WEAPONS LABORATORY, WECOM

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13. ABSTRACT

A program to evaluate the properties of prealloyed steel powders, consolidated by various fabrication techniques, was conducted under the direction of the Research Directorate, Weapons Laboratory, WECOM. Sixteen lots of low-alloy prealloyed steel powder, representing seven different major alloys (4130, 1040, 8620, 4640, 4650, 8650, and 9450) were formed into test specimens, heat treated, and tested. Processes used to fabricate the test specimens included die press and sinter, isostatic press and sinter, hot repress (limited deformation forging), and high-energy rate forming (HERF). With all fabrication procedures employed, commercial practice was closely adhered to; no attempt was made to optimize any given fabrication procedure. Tensile and impact property data, and the dependence of these values on fabrication and heat treatment parameters are presented. Specimens fabricated by hot repressing and HERF methods exhibited tensile and impact properties far superior to specimens fabricated by cold pressing and sintering. Optimization of the hot repress operation, to include improved oxidation protection during preform preheating and a greater degree of metal flow during pressing, should result in specimens exhibiting properties close to those normally associated with wrought materials. (U) (Westerman, R. E. and Sump, K. R.)

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- FINAL REPORT -

December 1972

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FOREWORD

This report was prepared by Dr. R. E. Westerman and K. R. Sump of the Pacific Northwest Laboratories, Battelle Memorial Institute, in compliance with Contract MIPR A1-1-50248-M1-Ws under the direction of the Research Directorate, Weapons Laboratory, WECOM, U. S. Army Weapons Command, with W. V. Cassell as project engineer.

The work was authorized as part of the Manufacturing Methods and Technology Program of the U. S. Army Materiel Command which is administered by the U. S. Army Production Equipment Agency.

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1. INTRODUCTION

The successful application of powder metallurgy fabrication techniques to ordnance components offers substantial economic incentives. In order to gain acceptance for such applications, powder metallurgy (P/M) products must demonstrate an overall utility and reliability comparable to that of the wrought or cast components they are intended to replace.

It is well known that products produced by conventional die press and sinter P/M fabrication techniques generally exhibit mechanical properties inferior to those of their wrought counterparts, because of the high concentration of pores within the bulk material. This problem can be minimized by employing fabrication procedures which lead to high densification, such as hot repressing and forging. Densification of the product is especially important when considering the fabrication of P/M components from high strength, heat treatable steels, as the high-strength characteristics of these steels are inefficiently utilized unless the density approaches the theoretical maximum. This makes the fabrication process, and the resulting compact density, extremely important considerations when optimum properties are sought in a given part.

The hot repressing and forging of steel P/M preforms is currently receiving a great deal of attention, particularly in the automotive industry. Improvements in powders, manufacturing procedures, and preform design are making the economic advantages of components produced in this fashion increasingly evident. A number of papers have been published which outline the economic advantages of high-strength hot repressed or forged steel P/M components and the problems involved in their manufacture, and which list some physical/mechanical properties of resulting parts or test pieces.[1-26]

The primary advantages of P/M hot repressing or forging over forging of wrought material are 1) a reduced number of fabrication steps, 2) material saving due to reduction of scrap loss, 3) reduced pressure requirement, and 4) reduced machining costs due to close tolerances and good surface finish. With proper preform design, appropriate powder

composition, caution in handling the preform to avoid contamination prior to forging, and a high degree of densification, mechanical properties approaching those exhibited by wrought materials can be obtained.

2. PROGRAM OBJECTIVES

The mechanical properties which can be obtained from heat-treatable steel P/M parts have not yet been adequately determined. There has been a lack of work and published data in this area, partly due to the proprietary nature of much of the advanced work currently in progress. Also, the work which has been published has been the result of a variety of evaluation procedures, frequently specialized, applied to parts or samples which have been fabricated by substantially differing fabrication techniques.

The limits of applicability of conventional P/M fabrication techniques have not been well defined, particularly as applied to prealloyed steel powders. Also, the use of specialized testing procedures, not typical of those commonly applied to wrought products, has given the design engineers little opportunity to compare the characteristics of P/M materials with those of wrought products.

The present program has four major objectives:

- To determine the physical and mechanical properties of P/M products made from a wide range of prealloyed steel powders and produced by conventional powder metallurgy fabrication techniques, viz., die press/sinter and isostatic press/sinter. Cold and hot repress operations are included in this series of tests.
- To determine the physical/mechanical properties of products of the same powders resulting from the more advanced high-energy-rate-forming (HERF) fabrication process. Resulting compacts approach theoretical density, and so can be considered close P/M analogs to wrought products.
- To investigate the influence of a range of hot repress fabrication parameters on a selected group of steel powders.

- To compare the results of the foregoing fabrication procedures, determine the utility of currently employed fabrication techniques as applied to prealloyed steel powders, and present the data in a form usable by designers. Available vendor data are also presented. Testing procedures used for wrought products have been applied throughout. Fabrication process/powder combinations yielding inferior properties are included in the presentation, to help define the limits of P/M process applications and to help form the foundation for future developmental work.

A total of sixteen different steel powders was employed in the fabrication processes. Of these, ten were totally prealloyed, and six were prealloyed with the exception of carbon. The broad spectrum of powders used assured the formation of valid general conclusions regarding the suitability of conventional P/M fabrication techniques as applied to alloy steel powders. All materials used are nominally heat treatable, and all samples were evaluated in the heat-treated (quenched and tempered) condition.

It must be emphasized that the objective of this program was not the optimization of P/M properties through development of powder compositions, preform designs, or fabrication procedures. Emphasis was placed instead on determining and cataloging properties obtained by applying more or less conventional P/M processing to a range of prealloyed powders. This permits the establishment of a P/M property baseline, so that the need for, or effects of, optimization may become apparent.

3. PROGRAM DESCRIPTION

This program is divided into three tasks. Each task will be briefly described in this section.

3.1 Task A

Task A was concerned with the basic application of the conventional die press/sinter process to prealloyed steel powders. Process parameters

were confined to compacting at 80 ksi and sintering at 2050°F, followed by a standard heat treatment procedure.

A total of eight powders was processed. Six were various modifications of type 4130, differing in mesh size, chemistry, and atomization technique. The remaining two powders were types 1040 and 8620, each totally prealloyed. The 8620 specimens were tested in the carburized (15-mil case) and heat-treated condition, with no surface preparation following carburization or heat treatment.

The green density and the sintered density were determined for each material. The Charpy V-notch impact strength and the room temperature tensile strength of the materials were determined after the sintering operation. A number of compacts produced in Task A were too fragile to handle, and so could not progress to the mechanical property determination stage, which necessarily involved machining and handling operations. Ability to withstand handling and machining was treated throughout this program as a qualitative material property.

The results of preliminary Task A studies on 4130 powder of three mesh sizes were used to define the most suitable mesh sizes of powders used in the next task (Task B), as well as the 1040 and 8620 powders included in Task A.

3.2 Task B

The P/M fabrication processes employed in this task were intended to extend beyond the limited Task A work, in that three major processes were to be employed: die press and sinter (with cold and hot repress), isostatic press and sinter (with cold and hot repress), and high-energy-rate-forming (HERF).

In the case of die pressing, three initial compaction pressures were used, two sintering temperatures, two hot repress temperatures, and a cold repress operation. The isostatic press process sequence was identical, with the exception that only one initial compaction pressure was used.

The HERF fabrication technique was restricted to two temperatures and two impact pressures.

Six powders were used in the major Task B study: a 4130 prealloy, processed throughout the entire fabrication procedure outlined above, and five "shelf item" prealloys, processed only through the die press/sinter operation outlined in the foregoing.

An important part of the Task B effort was termed the "Cursory Study," in which the subprocess of each major process (die press, isopress, HERF) which yielded the best mechanical properties using 4130 prealloyed powder was applied to four additional powders. By this means data on relatively high quality compacts were made available over a broader range of materials.

The density of all compacts resulting from all Task B processes was determined. The tensile properties and hardness were determined on all compacts except those resulting from the original compaction (green compacts). Impact properties were determined on all nonshelf-item powder compacts resulting from a "best process," and all shelf-item powder compacts resulting from an 80 ksi die compaction, 2050°F sinter process. This latter process was chosen to correspond with results of Task A impact tests.

All Task B Charpy tests were performed over a range of temperatures, from -40°F to 450°F.

3.3 Task C

The third part of the program, Task C, was primarily a hot repressing (limited deformation forging) investigation, to determine the influence of hot repressing temperatures and pressures on the mechanical properties of the resulting products. Four powders were selected for study, based on their behavior in the preceding task and overall programmatic considerations. Tensile and Charpy V-notch impact data were obtained on all samples. An additional tempering temperature was also investigated, viz., 1100°F, to gain additional tempering data; all previous samples had been tempered at either 900°F (noncarburized samples) or 450°F (carburized samples).

An overall outline of the program is shown in Figure 1. Detailed operational sequences and parameters have been omitted from this outline.

4. MATERIALS

4.1 Steel Powders

Materials used in the present study are described in detail in Figures 2, 3, 4, and 5. The shapes of typical as-received particles of each lot are shown in Figure 6.

The Hoeganaes -100 mesh 4130 (Code B) powder, water atomized and reduced, was the powder emphasized throughout the study. It was bought in two lots, B1 and B2, of somewhat different sieve analysis and chemistry. The two lots were later found to exhibit markedly different compaction characteristics.

The powders used in Task A are Codes A through H. The mesh size specification of powders A, B1, and C ranged from -40 to -200, for determination of the effect of this parameter on mechanical properties. They were derived from the same ingot, for control of chemistry. The final carbon level is controlled by the postatomization reduction process, and so does not depend on the carbon level in the original melt. Powders D through F were not reduced after atomization, and the atomization process itself varies from powder to powder as a process parameter.

The powders used in Task B include lots B1 and B2, plus F through N. Powders F, G, H, and I were used in the Cursory Study. Powder I, prealloyed 4100 with 0.3 percent carbon blended in, is included for comparison with the totally prealloyed 4130 powders.

Powders J through N are shelf item powders, included in the program for extension of available vendor data as well as to permit comparison of their properties with those resulting from the special heat powders which make up the remainder of the program. Powder J is completely prealloyed powder; the rest of this group require blending of appropriate amounts of carbon.

TASK	STEEL	CODE (LOT)	PROCESSING	DATA TENSILE	DATA IMPACT
A	4130	A B1,2 C	Compaction 80 ksi Sinter 2050°F with Standard heat treatment: Austenitize 1575°F, water quench temper for 1 hr at 900°F	X X X	X X X
		D E F		Compacts too fragile to handle	
	1040	G		X	X
	8620	H	Same as above, but carburized. Given standard heat treatment, except tempered at 450°F	X	X
B	4130	B1 B2	Die press (DP) Iso press (IP) HERF } standard heat treatment	X	
			One best process from each of above		X
CURSORY STUDY	4130	F	HERF only - standard heat treatment	X	X
	4100 + 0.3 C 1040	I G	One best process from each major process: DP, IP and HERF } - standard heat treatment	X	X
	8620	H	Same, except carburized to .15-mil case depth. Tempered at 450°F	X	X
	4650 4600 + 0.5 C 4600 + 0.5 C 8600 + 0.5 C 9400 + 0.5 C	J K L1 M N	Die press portion of Task B, with standard heat treatment	X	
			80 ksi compaction, 2050°F sinter, standard heat treatment		X
C	4130 4600 + 0.4 C 4650	B2 L2 J	Compact at 100 ksi, sinter 2050°F Hot repress at 80 ksi, 120 ksi, 160 ksi at 1800°F, 2000°F, 2200°F Austenitize, water quench, temper at 900°F and 1100°F	X X X	X X X
	8620	H	Same, except carburized, and tempered at 450°F and 900°F	X	X

FIGURE 1. Basic Outline of Powder Metallurgy Program

CODE		A	B1	B2	C
TYPE		4130	4130	4130	4130
VENDOR		Hoeganaes	Hoeganaes	Hoeganaes	Hoeganaes
PROCESS		water atomized, reduced	water atomized, reduced	water atomized, reduced	water atomized, reduced
MESH		-40	-100	-100	-200
Chemical Analysis, wt.percent	C	0.28	0.26	0.28	0.28
	Cr	1.00	1.00	1.00	1.00
	Mn	0.48	0.48	0.58	0.48
	Mo	0.21	0.21	0.23	0.21
	Ni				
	P				
	Si	0.40	0.40	0.20	0.40
	S				
	Fe	bal.	bal.	bal.	bal.
H_2 Loss percent			0.40	0.58	
Sieve Analysis wt.percent U.S. Standard	80	12.7	T*	T	T
	100		0.6	0.7	T
	140	26.7	8.7	13.4	T
	200	15.5	19.7	23.0	0.6
	230		6.4	6.4	1.1
	270				
	325	17.2	22.5	19.1	23.6
	-325	27.8	42.1	37.4	74.7
Apparent Density, gm/cm^3					

* T = Trace

FIGURE 2. Metal Powder Characteristics

CODE		D	E	F	G
TYPE		4130	4130	4130	1040
VENDOR		Glidden-Durkee	Federal-Mogul	Federal-Mogul	Hoeganaes
PROCESS		water atomized	water atomized	gas atomized	water atomized, reduced
MESH		-100	-100	-100	-100
Chemical Analysis, wt.percent	C	0.52	0.28	0.29	0.41
	Cr	0.94	1.02	1.09	
	Mn	0.58	0.56	0.40	0.81
	Mo	0.36	0.20	0.23	
	Ni				
	P		0.011	0.010	0.01
	Si	0.42	0.31	0.23	
	S	0.008	0.014	0.011	0.009
	Fe	bal.	bal.	bal.	bal.
H_2 Loss, percent					0.49
Sieve Analysis U.S. Standard	80				T
	100	0.3	3.7	2.5	1.0
	140	13.8	13.1	19.1	18.4
	200	18.4	17.1	20.5	28.2
	230				6.7
	270		15.4	12.6	
	325	28.2	9.1	11.5	19.8
	-325	39.3	41.6	33.8	25.9
Apparent Density, gm/cm^3					2.71

FIGURE 3. Metal Powder Characteristics

CODE		H	I	J	K
TYPE		8620	4100 + 0.30 C*	4650	4600 + 0.5 C*
VENDOR		Hoeganaes	Hoeganaes	Glidden-Durkee	Glidden-Durkee
PROCESS		water atomized, reduced	water atomized, reduced		
MESH		-100	-100	-100	-100
Chemical Analysis, wt.percent	C	0.20	0.30*	0.46	0.59*
	Cr	0.38	0.95		
	Mn	0.81	0.58	0.47	0.45
	Mo	0.24	0.23	0.23	0.27
	Ni	0.71	<0.05	1.94	1.99
	P				
	Si	0.26	0.19	0.49	0.30
	S		0.013	0.029	0.03
	Fe	bal.	bal.	bal.	bal.
H_2 Loss, percent					
Sieve Analysis U.S. Standard	80	T			
	100	0.5	T	2.7	1.4
	140	14.1	8.9	11.0	9.8
	200	26.2	23.8	13.4	13.4
	230	6.7	8.9		
	270				
	325	19.6	25.0	23.8	25.7
	-325	32.9	33.4	49.1	49.7
Apparent Density, gm/cm^3					

* Carbon blended separately

FIGURE 4. Metal Powder Characteristics

CODE		L1	L2	M	N
TYPE		4600 + 0.5 C*	4600 + 0.4 C†	8600 + 0.5 C*	9400 + 0.5 C*
VENDOR		A.O. Smith-Inland	A.O. Smith-Inland	A.O. Smith-Inland	A.O. Smith-Inland
PROCESS		water atomized, reduced	water atomized, reduced	water atomized, reduced	water atomized, reduced
MESH		-100	-100	-100	-100
Chemical Analysis, wt.percent	C	0.51*	0.41†	0.51*	0.51*
	Cr			0.60	0.31
	Mn	0.19	0.19	0.09	0.24
	Mo	0.46	0.46	0.49	0.30
	Ni	2.00	2.00	0.59	0.25
	P	0.005	0.005	0.007	0.008
	Si	0.027	0.027	0.018	0.05
	S	0.016	0.016	0.012	0.014
	Fe	bal.	bal.	bal.	bal.
H_2 Loss, percent		0.15	0.15	0.42	0.32
Sieve Analysis U.S. Standard	80			0.5	
	100	2.8	2.8	4.0	0.5
	140	17.1	17.1	13.5	14.6
	200	25.9	25.9	24.5	27.4
	230	4.9	4.9	6.0	6.4
	270				
	325	22.8	22.8	23.5	23.6
	-325	26.5	26.5	28.0	27.5
Apparent Density, gm/cm^3		2.93	2.93	3.29	3.13

* 0.50 wt.percent carbon blended separately
† 0.40 wt.percent carbon blended separately

FIGURE 5. Metal Powder Characteristics

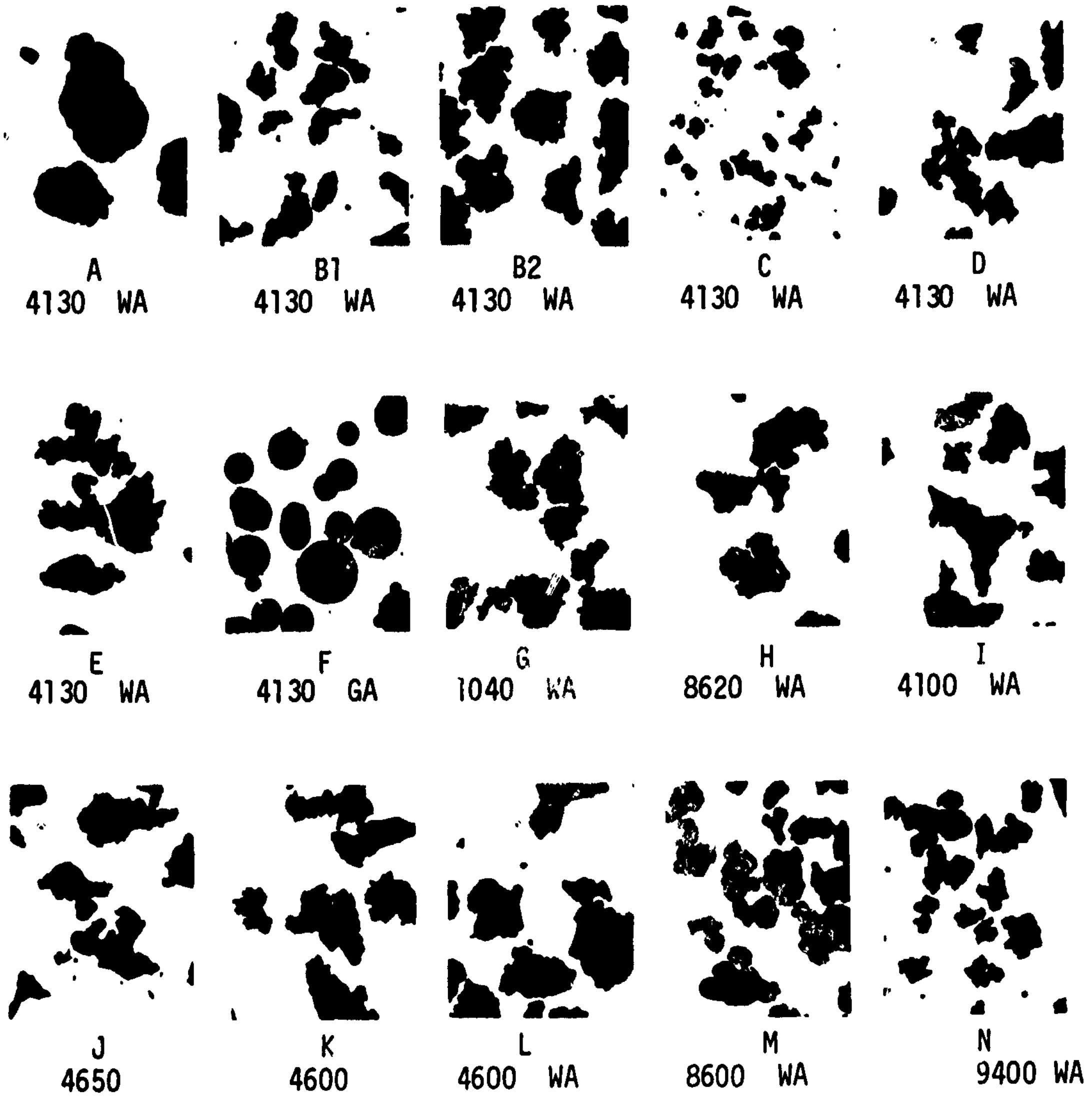


FIGURE 6. Prealloyed Powders Used in Program
WA = water atomized GA = gas atomized
50X

4.2 Carbon

The carbon used in this program is a product of Southwestern Graphite, Burnet, Texas. It is a natural graphite, of particle size 0.2 to 0.7 micrometer, designated Grade 1651.

5. PROCEDURES

5.1 Powder Preparation

Powder preparation involved the addition of a lubricant for cold pressing and the addition of graphite to adjust the carbon content of certain steel powders. No lubricant was required for the isostatic pressing and HERF processes. The blending of lubricant and/or graphite with the metal powders was done in a Hyde paint shaker. Powder, additive, and steel balls were loaded in a two-quart steel container and mixed for 15 minutes.

One-half weight percent of zinc stearate was added to all of the powders fabricated by cold pressing, with the exception of powders D, E, and F in Task A. These materials were difficult to press into coherent green compacts, so one weight percent zinc stearate was added to improve compact strength.

5.2 Die Pressing

Die pressing was the most common means of initial compaction employed in the present program, as it was used exclusively in Task A and was the principal initial compaction method used in Tasks B and C.

One of the punch and die sets used in the program is shown in Figure 7. The cavity of the die used in Tasks A and B is 1.125 in. wide, 4.225 in. long, and 3.000 in. deep. The cavity of the die used in Task C is 0.475 in. wide, 2.715 in. long, and 2.375 in. deep.

The 300-ton hydraulic press used in the die pressing operation is shown in Figure 8. The ram speed is approximately 400 in./minute.

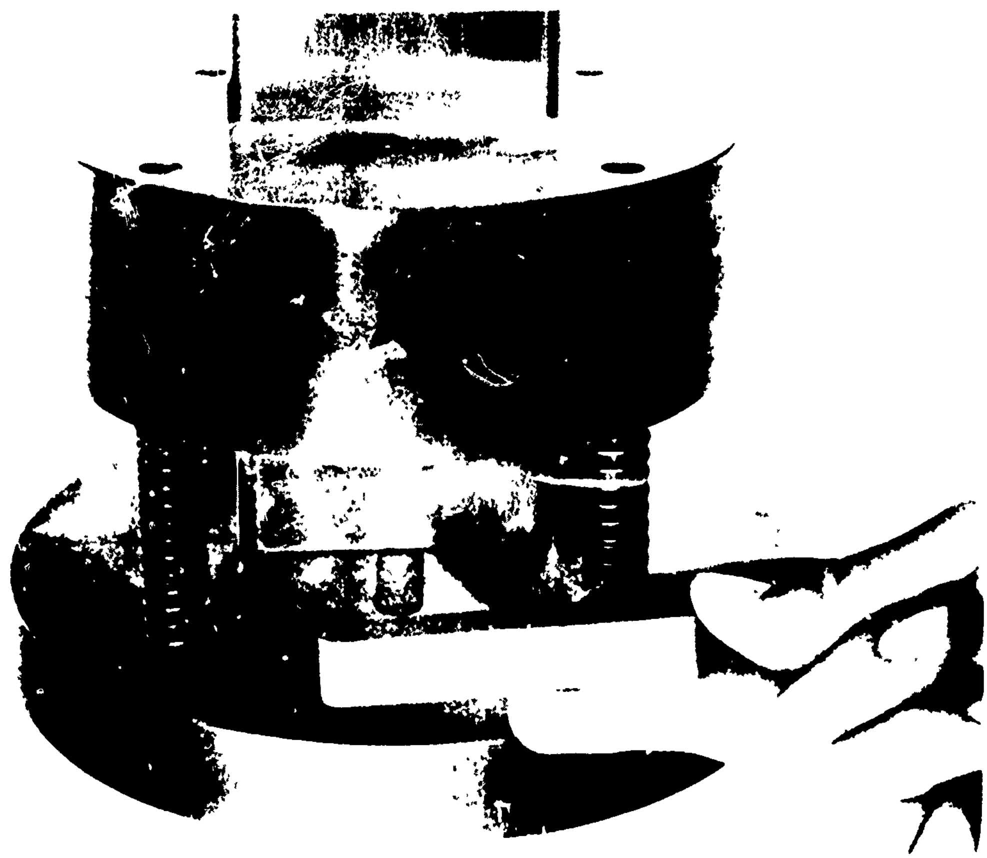


FIGURE 7. Die and Punches Used in Die Pressing Operation, with Typical Compact

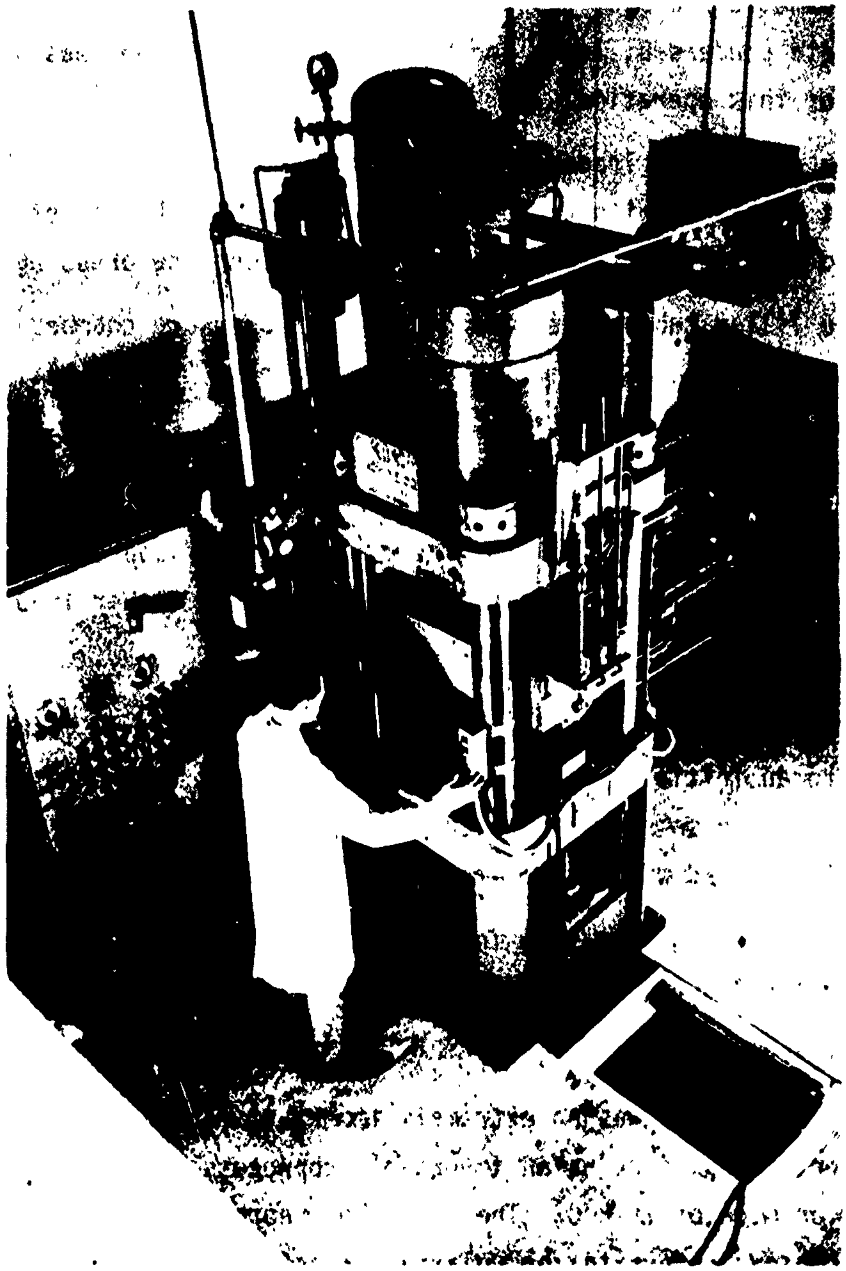


FIGURE 8. Hydraulic Press Used for Die Pressing and Forging

5.3 Isostatic Pressing

Isostatic pressing was one of the three principal methods used to consolidate powders B, I, G, and H in Task B. No binder was added to the powder for this operation.

The powder was loaded into thin wall rubber tubing, which was then sealed at both ends with a rubber cork (Figure 9). Pieces of angle iron were used to hold the filled tube straight during the pressing operation.

The filled tubes were loaded in a high pressure chamber (Figure 10), and compacted at 50,000 psi with pressurized oil. The resulting rods were approximately 12 in. long and 0.75 in. in diameter.

5.4 Sintering

The samples resulting from the die press and isopress operations were sintered for 1/2 hr in dissociated ammonia at either 1650 or 2050°F.

5.5 Cold Repress and Sinter

A cold repress and sinter operation was employed in Task B as a subprocess to an initial die press/sinter operation. The repressing was done at 80 ksi in the same die in which the initial die pressing was done. The die was lubricated with butyl stearate.

The sintering operation following cold repress was done at 2050°F for 1/2 hr in dissociated ammonia.

5.6 Hot Repressing

Hot repressing was an extremely important fabrication process in the current study, forming an important subprocess in Task B and the major fabrication mode of Task C. The term "hot repressing" as used in the present context refers to the uniaxial pressing of a heated preform in a close-fitting die with very little lateral metal flow. "Hot repressing" is synonymous with the terms "hot densification,"[1] "hot recompaction,"[2] "hot coining,"[3] or "hot restriking."[3] Hot repressing is not as effective as the more conventional forging processes in reducing the porosity of the preform, and so the impact and fatigue properties of parts

FIGURE 9. Powder-Filled Rubber Tubing Ready for Isostatic Pressing Operation

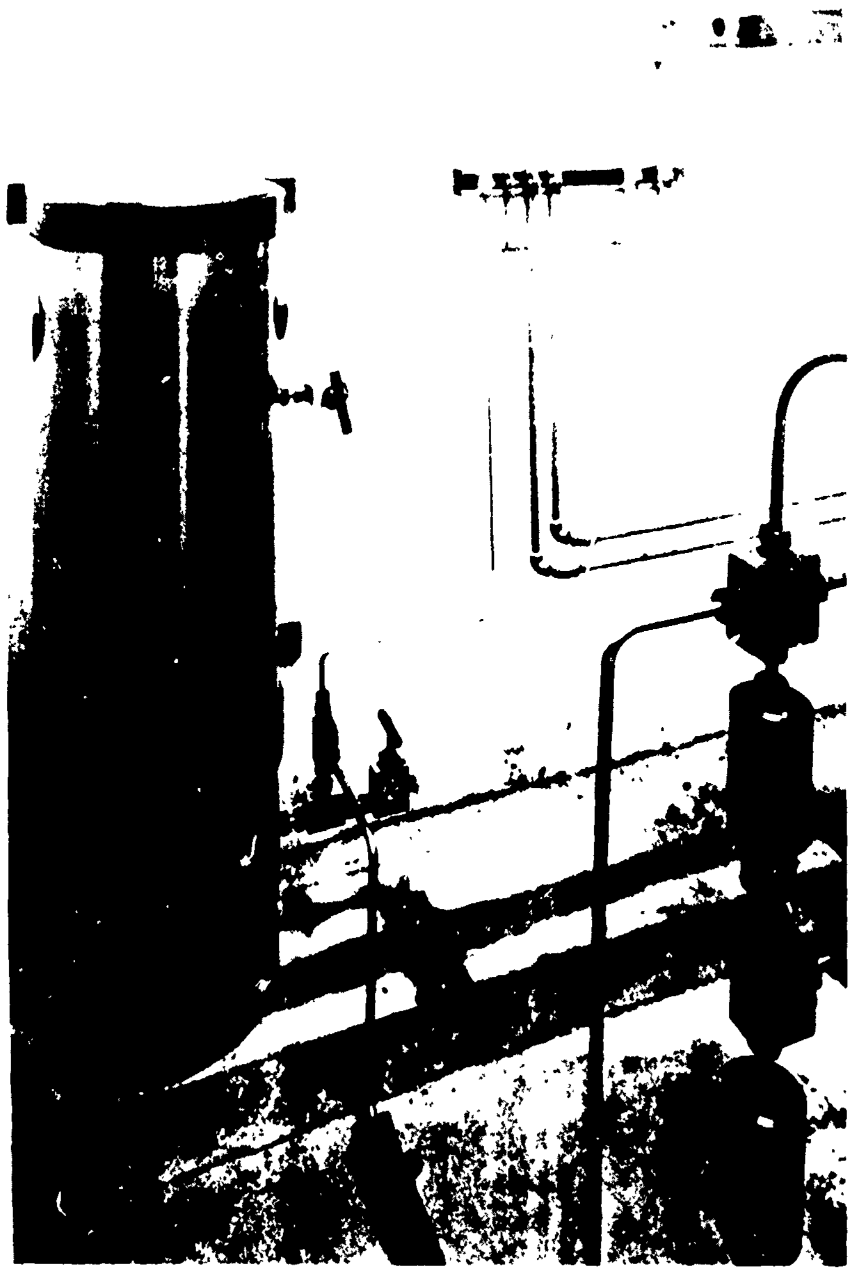


FIGURE 10. High-Pressure Chamber for Isostatic Pressing

made by hot repressing are lower than the properties of parts made by processes involving substantial metal flow.[4] Optimization of preform design and fabrication procedures (i.e., forging procedures) can yield parts having substantially better properties than those reported herein. Such optimization was beyond the scope of the present effort.

One of the hot repressing dies used in the program is shown in Figure 11. The hot repressing operations of Task B utilized a die having a cavity 0.565 in. wide, 4.000 in. long, and 1.300 in. deep. The hot repressing operations of Task C utilized a die having a cavity 0.503 in. wide, 3.750 in. long, and 1.250 in. deep. The dies are portable, with upper and lower punches. A commercial graphite-oil mixture was used for die lubrication.

The amount of deformation imposed on any given Task B preform during hot repressing is difficult to estimate, because the preforms varied somewhat in size and shape due to the different processes used to make the preforms, i.e., isostatic pressing and die pressing. Very little lateral flow occurred in any given case, however. In the case of Task C hot repressing, an average lateral flow of 6 percent and an average preform height reduction of 16 percent took place. The height reduction varied from 14 percent to 21 percent, depending on the preform density. Samples of H and L2 materials were the least compressible (14 percent reduction), samples of B and J the most (15 and 21 percent, respectively).

No preheating of the die was done in Task B except for buildup of heat from the hot preforms. The die was preheated to 800°F in the Task C work between each increment of approximately 10 repressing operations.

The hydraulic press shown in Figure 8 was used for all repress work.

Maximum hot repress pressure was held constant at 150 ksi throughout Task B; pressure was considered a variable in Task C. No control of punch motion was imposed beyond this pressure control.

5.7 High-Energy-Rate-Forming (HERF)

The HERF compaction process was the third principal compaction method used in Task B. This technique basically involves compressing a

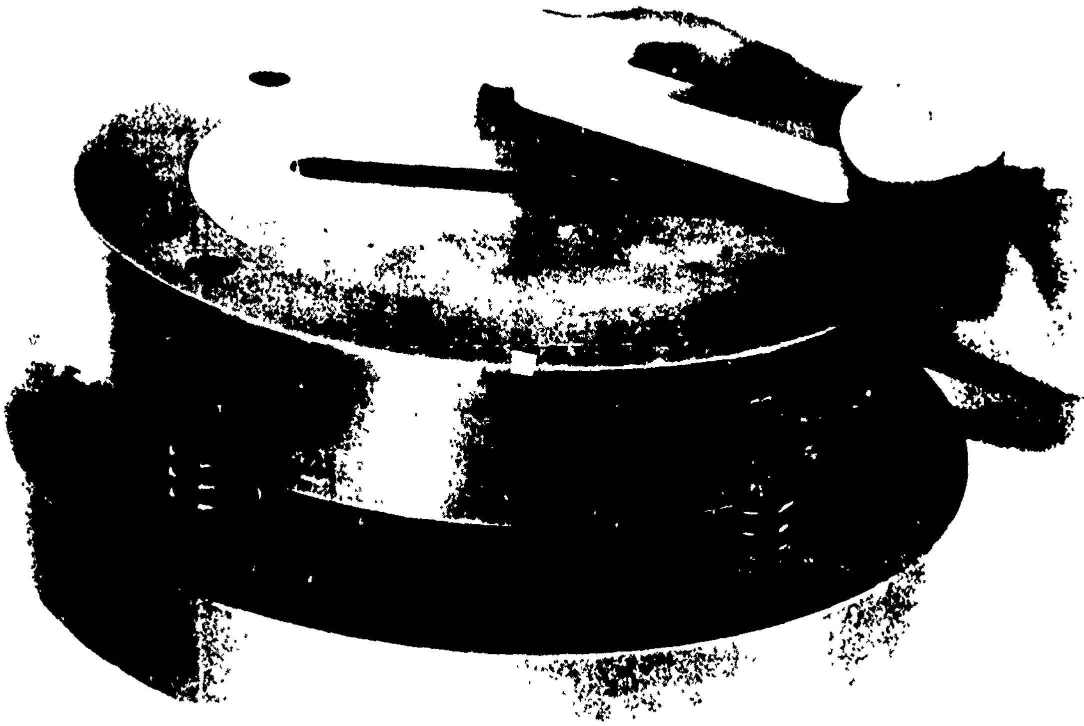


FIGURE 11. Die Used in Hot Repressing Operation, with Typical Bar

preheated powder in a closed die by a heavy ram traveling at high velocity. The ram deceleration produces very high compaction pressures (to 329 ksi in the present study) which, when imposed on a heated, highly plastic powder, allows attainment of densities close to theoretical.

The material to be densified was loaded into cylindrical stainless steel containers, 2 1/2 in. in diameter and 5 1/2 in. long. The first four billets compacted for Task B were made by pressing the powder into the containers. The remaining billets were made by loading the can with a cylinder of material preformed by isostatic pressing. This change facilitated loading and permitted loading more material into the can, resulting in a larger end product. A lid having an outgas stem was welded on each container (Figure 12).

The containers were evacuated during the period of preheating (approximately 1 hr). Two preheat temperatures were used: 1800°F and 2200°F. After the preheat temperature was attained the outgas tube was cut and sealed and the container transferred to the cylindrical closed die of the impaction machine, a Dynapak Model 1220B (Figure 13). Impaction pressures ranged from 172 ksi to 329 ksi. After compaction the billet was ejected from the die and allowed to cool. The container shell was removed by machining, and the cylindrical compact was sliced longitudinally into 1/2 in. thick slabs for heat treatment and machining.

5.8 Heat Treating and Carburizing

All of the steels included in the program can be considered hardenable to some practical extent, so that the mechanical properties of all of the compacts produced can be improved, at least in principle, by an austenitizing, quenching, and tempering sequence. A standard heat treatment was desired which would take advantage of the innate compact hardenability while not contributing excessively to compact brittleness. To accomplish this, a hardness of R_c 40 in the 4130 steel compacts was the heat treatment goal decided on. Compacts of Lot A 4130 steel, 1/2 in. thick, were austenitized at 1575°F in an endothermic gas atmosphere (+70°F dewpoint), quenched in still water at room temperature, and

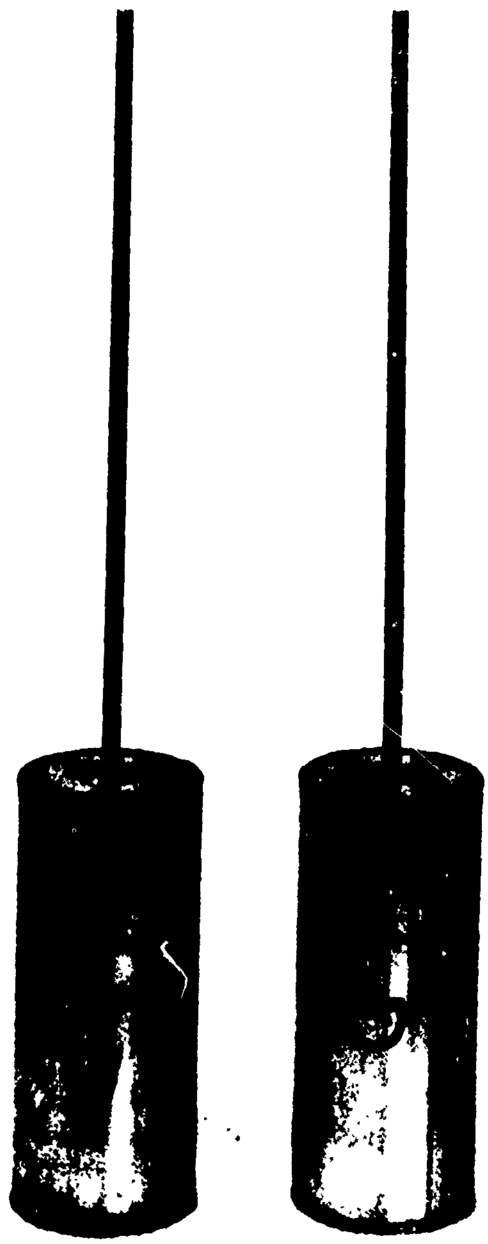


FIGURE 12. Powder Containers for HERF Process, with Outgassing Stems

FIGURE 13. Model 1220B Dynapak

tempered at various temperatures for 1 hr. They were then subjected to microhardness (DPH, 100 gm load) traverses, from surface to center of the sample over major particle clusters. A 900°F temper was found to produce the required hardness level. Wrought standards of 4130 yielded the same R_C 40 value. All of the compacts in the program were given this standard heat treatment just prior to specimen machining. All sample blanks in the program were approximately 1/2 in. thick when heat treated, so that the central hardenability of a 1/2 in. thick infinite plate represents a "worst case" situation for heat treatment response.

The 8620 steel (Lot H) was an exception to the standard heat treatment procedure described in the foregoing. This material was always machined into tensile and Charpy V-notch specimens after compact fabrication, then pack carburized in Woodside's Rapid Carburizer* at 1700°F for 2 hr and allowed to cool. The specimens were then austenitized at 1575°F for 1/2 hr in endothermic gas having a dewpoint of 10°F, oil quenched, and tempered for 1 hr at 450°F (Task B) or 450°F and 900°F (Task C). The resulting carburized case was approximately 15-mil thick on the high density samples, somewhat thicker on the less dense material.

Because of the range of carbon and alloy content of the steels used in the program, a considerable variation of hardnesses, hence mechanical properties, were expected to result from the standard heat treatment universally employed, and this was found to be the case. The other acceptable alternate which could be employed for purposes of comparing steel powders, viz., hardening each steel to the same hardness by varying the tempering temperature to fit the individual steel, was beyond the scope of the present program. In addition, the hardness level was considered to be no more fundamental a parameter than the tempering temperature when the purpose of a study is to provide property data for designers, especially if data over a range of tempering temperatures are to be eventually obtained.

* Product of the Park Chemical Company.

5.9 Density Measurements

All density measurements were bulk densities determined from physical measurements and weights of the samples. Densities were taken after each process step prior to heat treatment, and are all expressed in grams per cubic centimeter. Densities obtained in this manner are somewhat lower than true sample densities, because of inevitable sample surface irregularities.

5.10 Mechanical Testing

Tensile Properties

The tensile properties of the P/M products were determined by testing tensile specimens machined from the heat-treated compacts. Button-head specimens of a special design were employed throughout the program. The dimensions of the standard specimen are given in Figure 14.

The specimens were tested at room temperature in an Instron tensile test machine at a crosshead speed of 0.050 in./min. Elongation was determined over a one-inch portion of the central gage length by means of a high-sensitivity carbide-tipped extensometer.

Breakage outside of the reduced central section was common with many of the powders used, indicating a high sensitivity to surface effects and a low fracture toughness.

Machinability of the P/M products into tensile specimens was considered a basic qualitative material property. In general, duplicate P/M blanks were submitted for machining with instructions to produce two tensile specimens. If both blanks broke, machining of that particular specimen was not attempted again, and no tensile data were recorded. Duplicate tests were attempted on all tensile evaluations.

Where yield strength (YS) data are reported, it always indicates the 0.2 percent offset yield strength. This YS frequently could not be obtained, because limited sample elongation would not permit an extrapolation of the offset line to intersect the stress-strain curve. Absence of YS data can generally be inferred to indicate that lack of sample

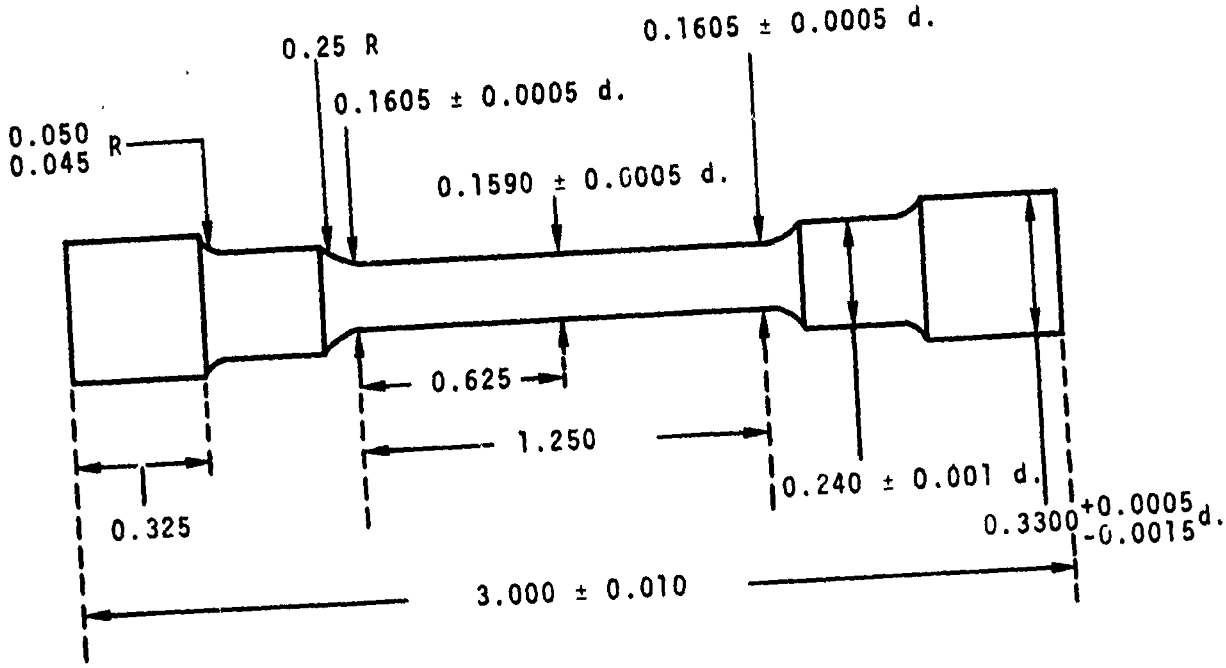


FIGURE 14. Button Head Tensile Specimen with Tapered Gage Section

ductility is at fault, though for two steels (Lots J and K) the YS data is not reported for some specimens because of erratic extensometer behavior.

Impact Properties

Selected P/M products were machined into Charpy V-notch specimens according to ASTM specifications A370, sample type A. Four test temperatures were used in the Task B studies: -40°F, 77°F, 210°F, and 450°F. In Task C all specimens were tested in duplicate at room temperature.

Hardness

The hardness of all specimens was determined after heat treatment. Two Rockwell scales were used: R_C, using a Brale indenter and a 150 kg load, and R_B, using a 1/16-in. ball and a 100 kg load. The hardness determined by these techniques is of course an apparent hardness only, as the hardness of individual particles, or grains, is not being reported, but rather the hardness of the metal-void composite structure.

6. RESULTS AND DISCUSSION

6.1 Task A

Lots A, B1, and C of 4130 Hoeganaes water-atomized and reduced powders were compacted at 80 ksi, sintered at 2050°F, machined into tensile and Charpy V-notch specimens, and tested. The results of this initial portion of Task A were to be used to define the mesh size of the 1040 and 8620 powders also included in Task A, and also the 4130 powder mesh size to be carried into Task B. Results of a number of tensile tests (approximately ten per lot) are shown in Figure 15.

The -200 mesh material (Lot C) demonstrated the highest average UTS, 60.6 ksi; the -100 mesh material (Lot B1) was slightly lower, with an average UTS of 58.2 ksi. On a strictly comparative basis, the -200 mesh was slightly superior; this advantage, however, was felt to be offset by the fact that -200 mesh material is not as commonly used in the P/M fabrication industry as -100 mesh. For this reason the somewhat superior

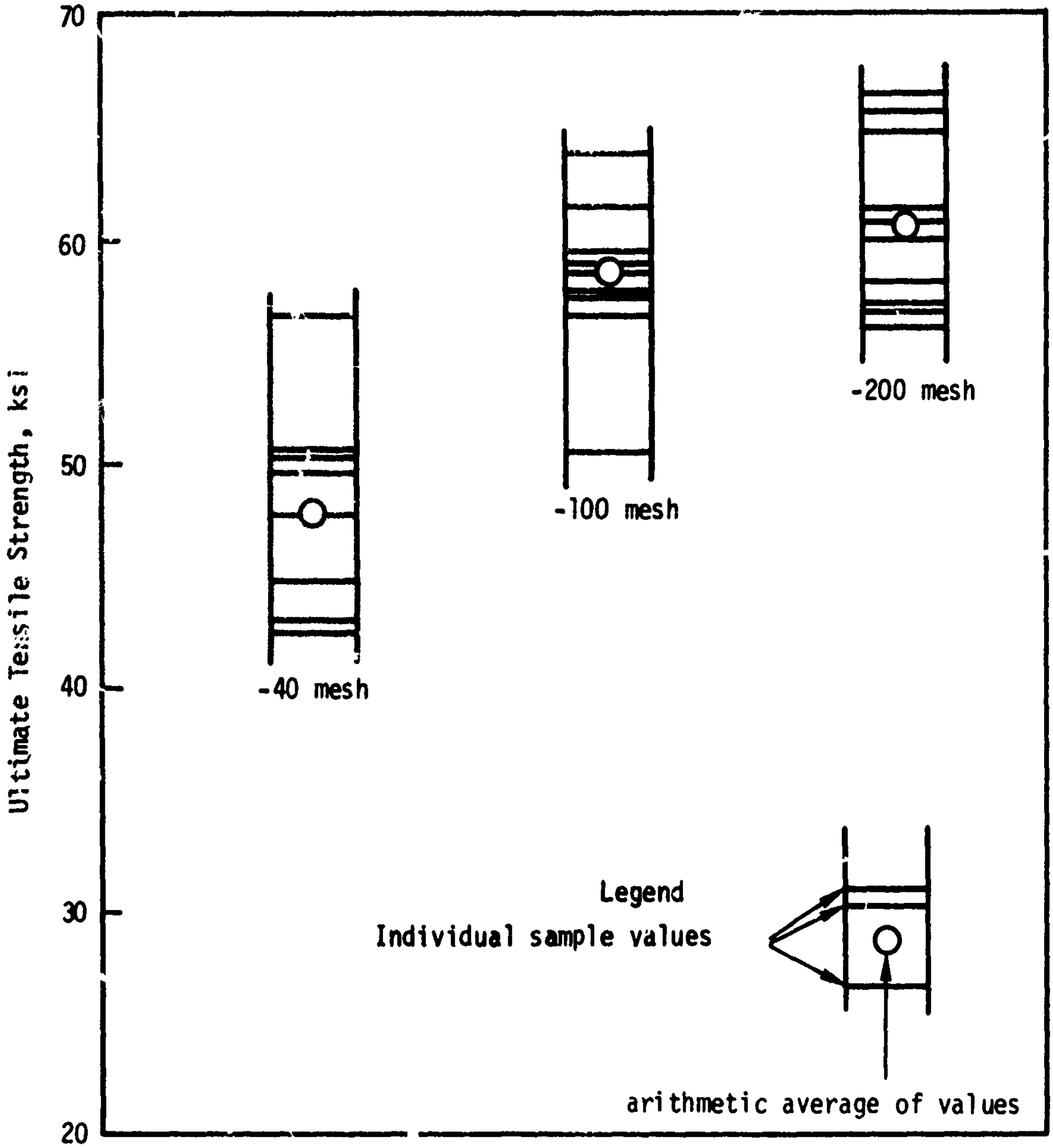


FIGURE 15. Influence of Mesh Size on Ultimate Tensile Strength Hoeganaes AISI 4130 Powder (A, B) Compacted at 80 ksi, Sintered 2050°F Task A

behavior of -200 mesh material was discounted and the decision made to carry through with -100 mesh material.

The water atomized and reduced powders A, B, and C demonstrated good compaction properties. The sintered bars were strong, could be handled roughly, and machined readily. In contrast, compacts produced from the nonreduced materials D, E, and F were too fragile to handle, even after sintering; their densities were low, 5.2 to 5.6 gm/cm^3. Lot F was carried into the HERF portion of the Cursory Study of Task B; powders D and E were not studies further.

The significant data of Task A are summarized in Figure 16. The table is incomplete, in that yield strength and hardness data are not included. These values may be found in the data compilation appended to the end of the report.

Data for Lots A and C will not be found in this report beyond Figure 16.

Powder Lot B2 was purchased when Lot B1 became exhausted. Lot B2 was found to be more easily compacted than Lot B1; this is evident from the data of Figure 16, and was found to be true whenever a compressibility comparison was made.

The Charpy impact values reported in Figure 16 are an order of magnitude lower than would be expected from wrought products of the same materials hardened to R_c 40. No increased impact energy absorption is evident when the temperature of testing is increased. Powder Lots A, B, and C show no significant difference in impact properties.

6.2 Task B

The Hoeganaes 4130, -100 mesh, water-atomized and reduced steel powder designated "Lot B" was the key powder in the program, in that the processes yielding the best results in this powder were applied, in the Cursory Study, to a broader range of powders. Also, it was processed and tested far more extensively than any other powder in the program. For these reasons, the Task B results obtained using this powder will be

CODE	STEEL	DENSITY gm/cm3	UTS ksi	TOTAL EL., %	CHARPY V-NOTCH IMPACT ENERGY, ft-lb			
					-40°F	77°F	210°F	450°F
A	4130	6.40	47.8[a]	0.43[a]	1.0	1.0	0.8	0.8
B1	4130	6.45	58.2[a]	0.64[a]				
B2	4130	6.60			1.0	0.9	1.0	0.8
C	4130	6.40	60.6[a]	0.73[a]	1.0	1.0	1.0	0.7
G	1040	6.72	40.0	5.1	1.7	2.0	2.0	1.8
			40.0	5.1				
H[b]	8620[b]	6.67	57.5	0.3		1.0		0.8
			55.6	0.3				

a - Arithmetic average of approximately 10 specimens.

b - Carburized, 15-mil case; tempered 450°F, instead of 900°F.

FIGURE 16. Data Summary, Task A. Powders compacted at 80 ksi, sintered 2050°F, austenitized 1575°F, water quenched, tempered at 900°F.

presented first. The results obtained in the application of the "best processes" to powders F, I, G, and H in the Cursory Study will be presented next. The final Task B discussion will involve the results obtained from the "shelf item" powders J, K, L, M, and N.

4130 (Lot B) Powder, Die Press

This powder was processed by three principal initial fabrication procedures: die press/sinter, isostatic press/sinter, and HERF. The die press results will be described first.

The die press/sinter procedure consisted of three initial compaction pressures. 50 ksi, 80 ksi, and 100 ksi.

Each of these initial compaction processes was followed by one of two sintering temperatures: 1650 or 2050°F.

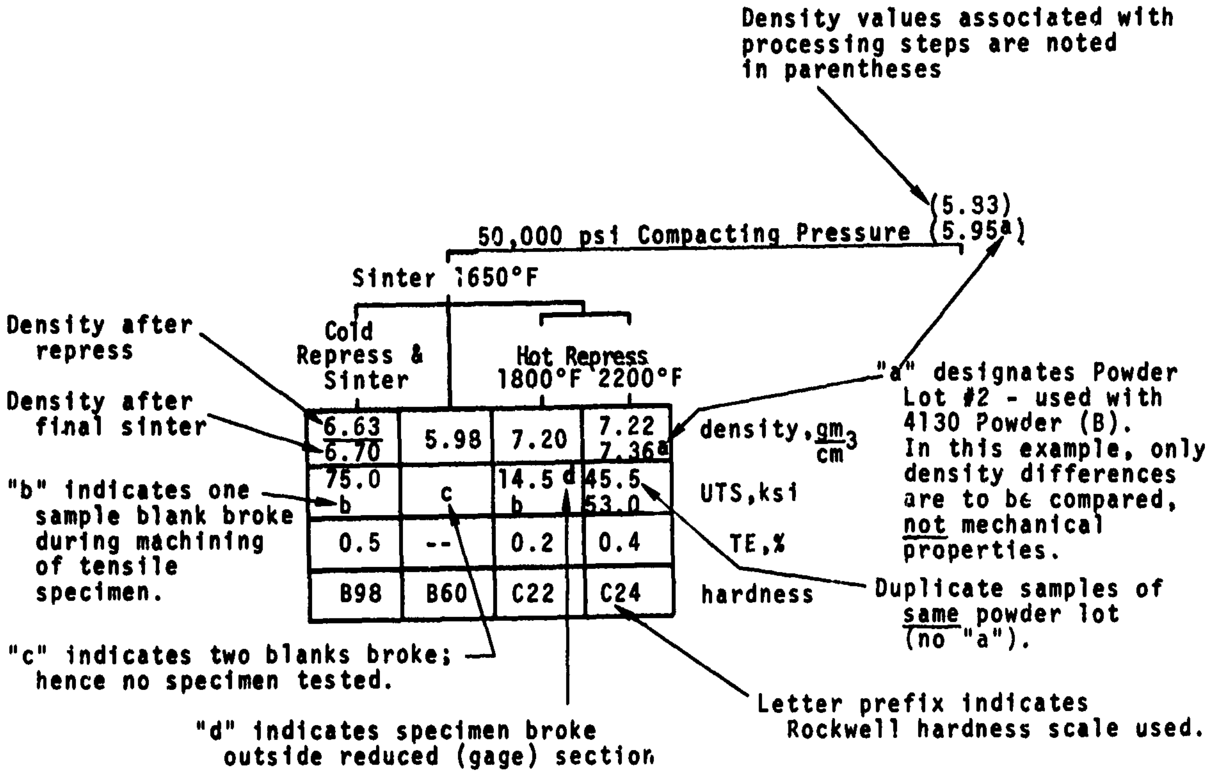
Each combined die press/sinter operation described above was followed by either a cold repress (80 ksi) and sinter (2050°F), or a hot repress (150 ksi, at either 1800°F or 2200°F).

The results of the die press processing of 4130 Lot B powder is presented in Figure 17 in a fashion which reveals the change in mechanical/physical properties as the processing progresses. A guide to assist in understanding the data presentation precedes the figure. Yield strength values have been omitted; they may be found in the handbook section appended to the report.

All mechanical property data presented have been derived from powder Lot B1. Lot B2 data is included for compressibility comparisons only. Note that use of B2 leads to higher density compacts.

High initial compaction pressures (100 ksi) coupled with high temperature forging (2200°F) yield the best properties. The cold repress and sinter operation contributes substantially to the mechanical properties of the sintered compacts. As expected, the compact initially pressed at 50 ksi and sintered at 1650°F has the lowest density and hardness values.

None of the blanks simply sintered at 1650°F without repressing survived the tensile specimen machining operation.



Guide to Understanding Data Presented in Figure 17

50,000 psi Compacting Pressure (5.81)

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm³	6.55 6.60	5.83	7.05	7.18	6.51 6.55	5.97	7.08	6.98
UTS, ksi	69.5 67.5	c	13.8[d] b	41.4[d] 103	61.6 58.3	21.7[d] 35.0	70.8 52.8	126 67.6
TE, %	0.4 0.4	---	0.1	0.3 3.4	0.4 0.3	0.3 0.2	0.5 0.2	2.5 0.3
hardness	B99	B58	C20	C27	B99	B78	C23	C27

80,000 psi Compacting Pressure (6.27)

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm³	6.82 6.85	6.31	7.00	7.29	6.72 6.66	6.43	7.11	7.08
UTS, ksi	81.0 91.4	c	47.0 47.5	126 b	70.4 b	57.2 53.7	97.5 96.5	131 85.2
TE, %	0.9 1.0	---	0.2 0.2	0.4	0.4	0.4 0.4	0.4 0.4	0.5 0.5
hardness	B99	B76	C25	C32	B94	B85	C28	B99

100,000 psi Compacting Pressure (6.48)
(6.78)[a]

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm³	6.95 6.89	6.52	7.16	7.21	6.90 6.90	6.65 6.83[a]	7.11	7.25 7.49[a]
UTS, ksi	89.9 94.6	c	41.4 54.5	118[d] 145	89.9 82.5	61.0 57.3	94.5 93.0	152 121
TE, %	0.6 0.6	---	0.1 0.2	--- 1.4	0.7 0.4	0.5 0.4	0.4 0.2	1.8 1.1
hardness	B94	B67	C20	C29	B98	B91	C27	C31

"Best Process"

a - Powder Lot #2. Density comparisons only.
b - One compact broke during machining.
c - Two compacts broke during machining.
d - Broke at shoulder.

FIGURE 17. Task B: Results of Die Press Processing of Hoeganaes Type 4130 Powder (B)

Several samples broke outside the reduced gage section, indicating the presence of stress concentration sites and low resistance to crack propagation. The total elongation (TE) is an order of magnitude below that which would be expected from wrought material of the same composition subjected to the same heat treatment.

Microstructures of pressed-and-sintered and hot repressed samples of Lot B1 material are shown in Figure 18.

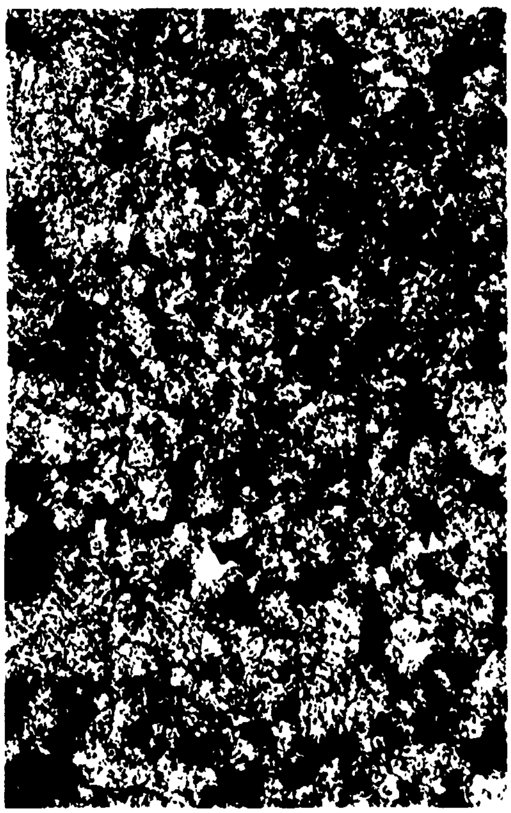
4130 (Lot B) Powder, Isostatic Press

The isostatic press procedure consisted of only one initial compaction pressure, 50 ksi. This was followed by either sintering at 1650°F, sintering at 2050°F, forging at 1800°F, forging at 2200°F, or a combined sinter-forge processing. Results of the tests, and changes in mechanical properties with processing parameters, are shown in Figure 19. Yield strength data may be found in the appendix. Lot B2 data is included for density comparisons only.

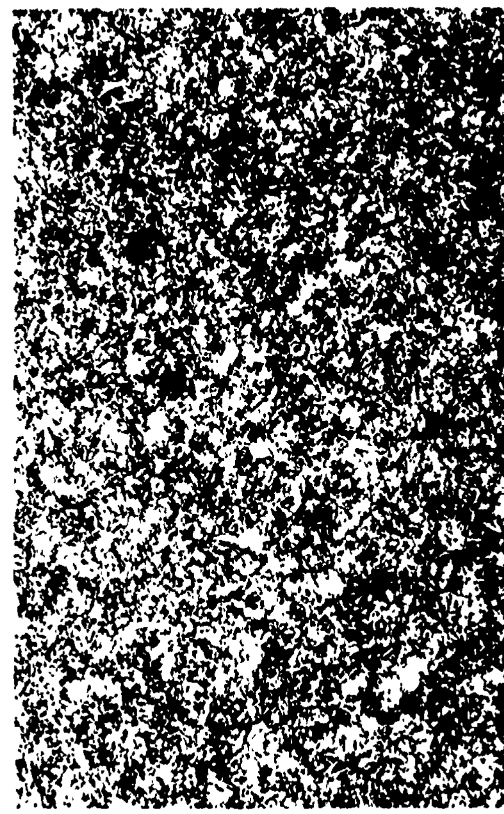
Based on tensile properties, hot repressing at 2200°F once again results in the best product, but the sintering temperature is the lower one employed, 1650°F. Once again, total elongation is low, and somewhat lower than that found in the die press "best process" (Figure 17), though the UTS values are somewhat higher. Also, the apparent hardness and density of the isopress material is higher than the die press material. The reason for this is not known.

Based on the limited data of Figure 19, the contribution of the intermediate sinter to the final forging properties can be considered to be minimal.

It was noted that a number of the more porous specimens tested up to this point in Task B had considerable internal oxidation. This was found to occur during the 900°F temper in air. To determine whether or not this oxidation was exerting undue influence on the mechanical properties of the samples, a number of representative compacts were made up, tempered in a high vacuum furnace instead of the circulating air furnace usually



Compacted 100 KSI
Sintered 2050 °F
Austenitized, Quenched
Tempered 900 °F
Density: 6.65 gm/cm^3



Compacted 100 KSI
Sintered 2050 °F
Hot Repressed 100 KSI at 2200 °F
Austenitized, Quenched
Tempered 900 °F
Density: 7.25 gm/cm^3

FIGURE 18. Microstructures of Die Pressed and Hot Repressed Samples of 4130 Powder (B1) 250X

4130 Powder (B)

Isostatic Press, 50,000 psi (5.90) (6.23)[a]

	Sinter 1650°F	Sinter 2050°F	Hot Repress 1800°F	Hot Repress 2200°F	Sinter 1650°F (6.06) (6.28)[a], Hot Repress 1800°F	Sinter 1650°F (6.06) (6.28)[a], Hot Repress 2200°F	Sinter 2050°F (6.18), Hot Repress 1800°F	Sinter 2050°F (6.18), Hot Repress 2200°F
density, gm/cm^3	6.06 6.28[a]	6.18	7.51	7.77	7.39	7.53 7.66[a]	7.40	7.44
UTS, psi	c	49.0 51.1	130[b]	140[b]	97.5 74.5	159 147	115 105	124 138
TE, %	-	0.5 0.5	0.5	0.8	0.5 0.3	0.5 0.5	1.3 0.7	0.6 1.1
hardness	B75	B81	C33	C37	C32	C39	C36	C37
						"Best Process"		

a - Powder Lot #2. Included only for density comparisons.
b - One sample broke during machining.
c - Two samples broke during machining.

FIGURE 19. Task B: Results of Isostatic Press Processing of Hoeganaes Type 4130 Powder (B)

used, and tested. No significant difference in mechanical properties was found, exonerating the air temper procedure.

4130 (Lot B) Powder, HERF

The HERF processing consisted of two impact pressures and two preheat temperatures. The resulting properties are shown in Figure 20. Mechanical property data were obtained from both lots of powder B1 and B2.

The "best process" was found to result from a 275 ksi compaction pressure and a 2200°F powder preheat, using Lot B1 powder. This hardened to R_C 35, as expected. This billet, however, was the first and only billet produced by the 2200°F preheat procedure to respond satisfactorily to heat treatment. Three other attempts (see Figure 20) failed to attain the hardness levels expected. The microstructure of the "soft" materials appears to be primarily tempered martensite, so that the best reason that can be advanced at present for the soft material is carbon (or other alloy element) loss during the preheat procedure. This failure to harden properly clouds the results of this portion of the investigation. Note the low total elongation found, even in the case of the softer material, in spite of the very high densities obtained by HERF processing.

The microstructure of the "best process" billet which hardened satisfactorily is shown in Figure 21, along with a micrograph of a billet of Lot B2 material which did not harden satisfactorily. Note the presence of some inclusions in the structures. Presence of such inclusions was found to be typical of all of the HERF microstructures examined.

4130 (Lot B) Powder: Impact Properties

Charpy V-notch impact properties were determined for all of the "best process" materials; these data are summarized in Table I.

The HERF impact data are surprisingly low, considering the density of the product and its relative softness (R_C 23). The die press and isopress best process materials are substantially better than the Task A material, though they fall far short of wrought properties.

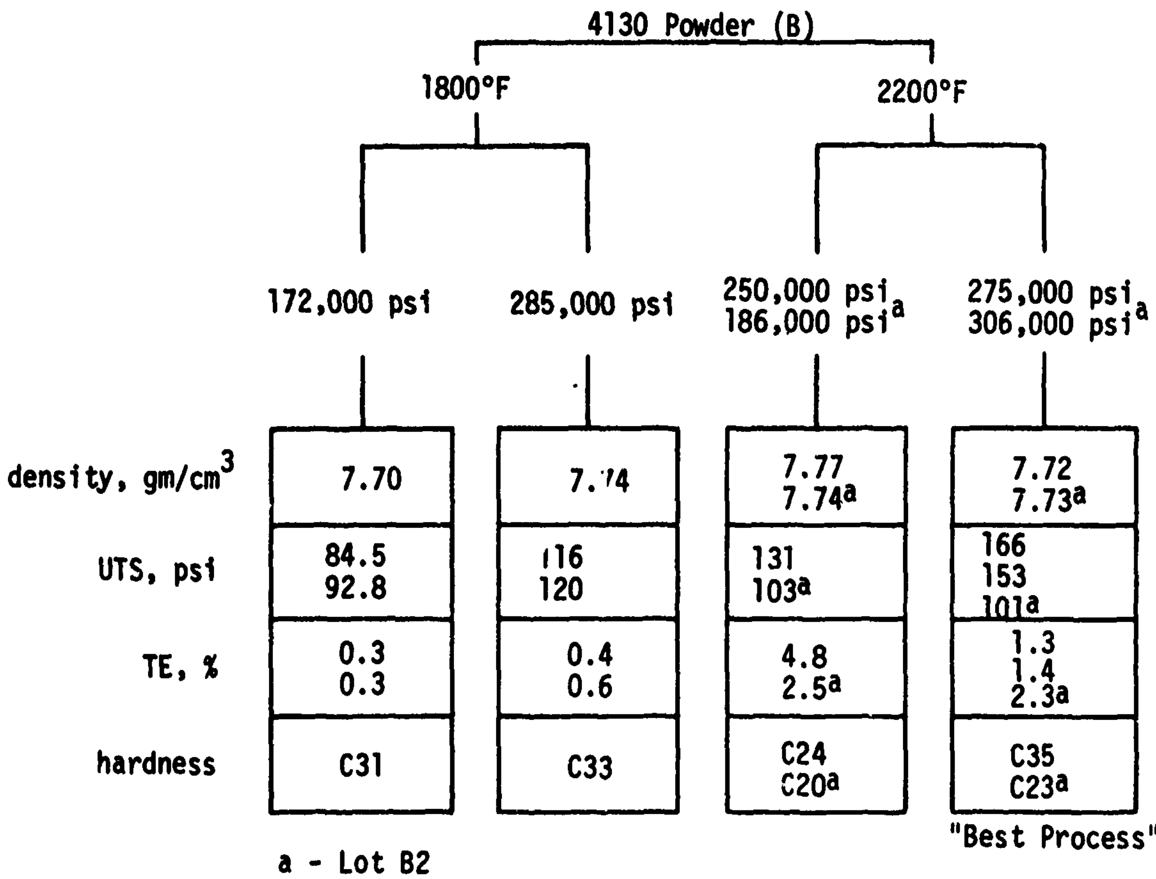


FIGURE 20. Task B: Results of HERF Processing of Hoeganaes Type 4130 Powder

Lot B1, "Best Process"
Hardness After
900 °F Temper: C35

Lot B2, "Best Process"
Hardness After
900 °F Temper: C23

FIGURE 21. Microstructures of HERF Processed Billets of 4130 Powder, Lots B1 and B2 250X

TABLE 1

Charpy V-Notch Impact Properties of Specimens Produced from 4130 Lot B Powder by "Best Processes"

	Impact Energy, ft-lb			
	-40°F	77°F	210°F	450°F
Die Press	4.5	3.2	7.3	5.9
Isopress	1.0	2.3	2.1	6.2
HERF	1.7	1.3	1.2	1.3

Cursory Study

The "best processes" outlined in the foregoing section (see Figures 17, 19, and 20) were applied to four powders beyond 4130 Lot B, viz., Lots F, I, G, and H. The properties resulting from these processes are shown in Figures 22, 23, 24, and 25, respectively. Yield strength data may be found in the appendix.

Powder Lot F is a gas-atomized, nonreduced prealloyed 4130 powder mentioned in the Task A discussion. It was only processed by HERF in the present study. Comparing the data of Figures 22 and 20 reveals that Lot F is definitely inferior to HERF-processed Lot B in terms of UTS and TE. Comparing the prealloyed 4100 with 0.3 C added (Lot I) of Figure 23 with the results of completely prealloyed Lot B (Figures 17, 19, and 20) we find that Lot B is generally superior (except for the greater TE exhibited by Lot I in the die press best process) even though Lot I material generally exhibits the greater density.

The mechanical properties of the 1040 powder (Lot G) are presented in Figure 24. This material exhibited unusually high densities, elongations and impact properties, and an unusually low hardness in the heat-treated condition.

4130 Gas-Atomized Powder (F)

High-Energy-Rate-Formed
~310,000 psi at 2200°F

density, gm/cm^3	7.80
UTS, ksi	77.0
TE, %	0.2
hardness	C32
Charpy impact R.T., ft-lb	1.6

FIGURE 22. Cursory Study: Results of HERF Processing of Gas-Atomized Federal-Mogul Type 4130 Powder (F)

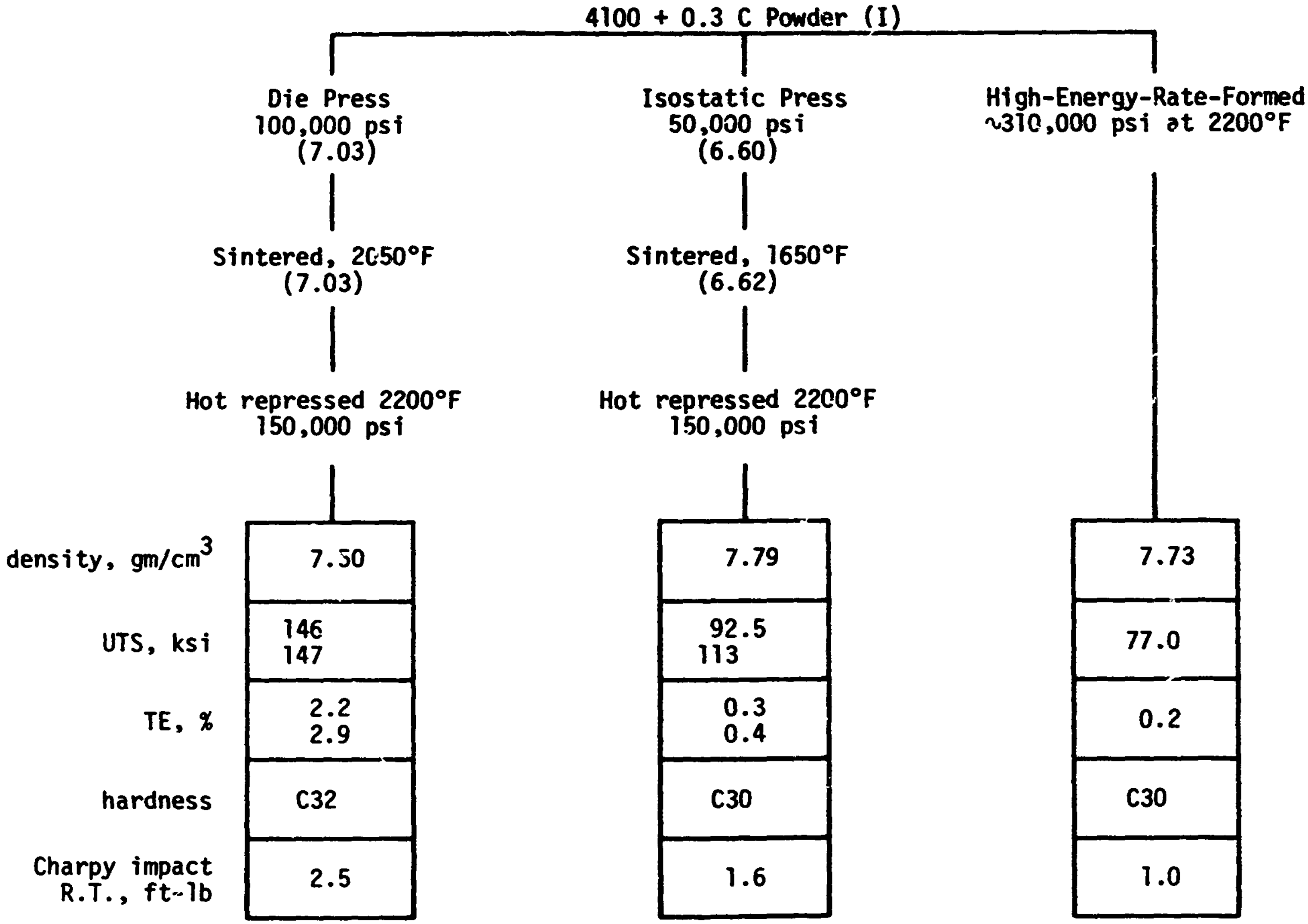


FIGURE 23. Cursory Study: Results of Best Processes, Hoeganaes Type 4100 + 0.3 C Powder (I)

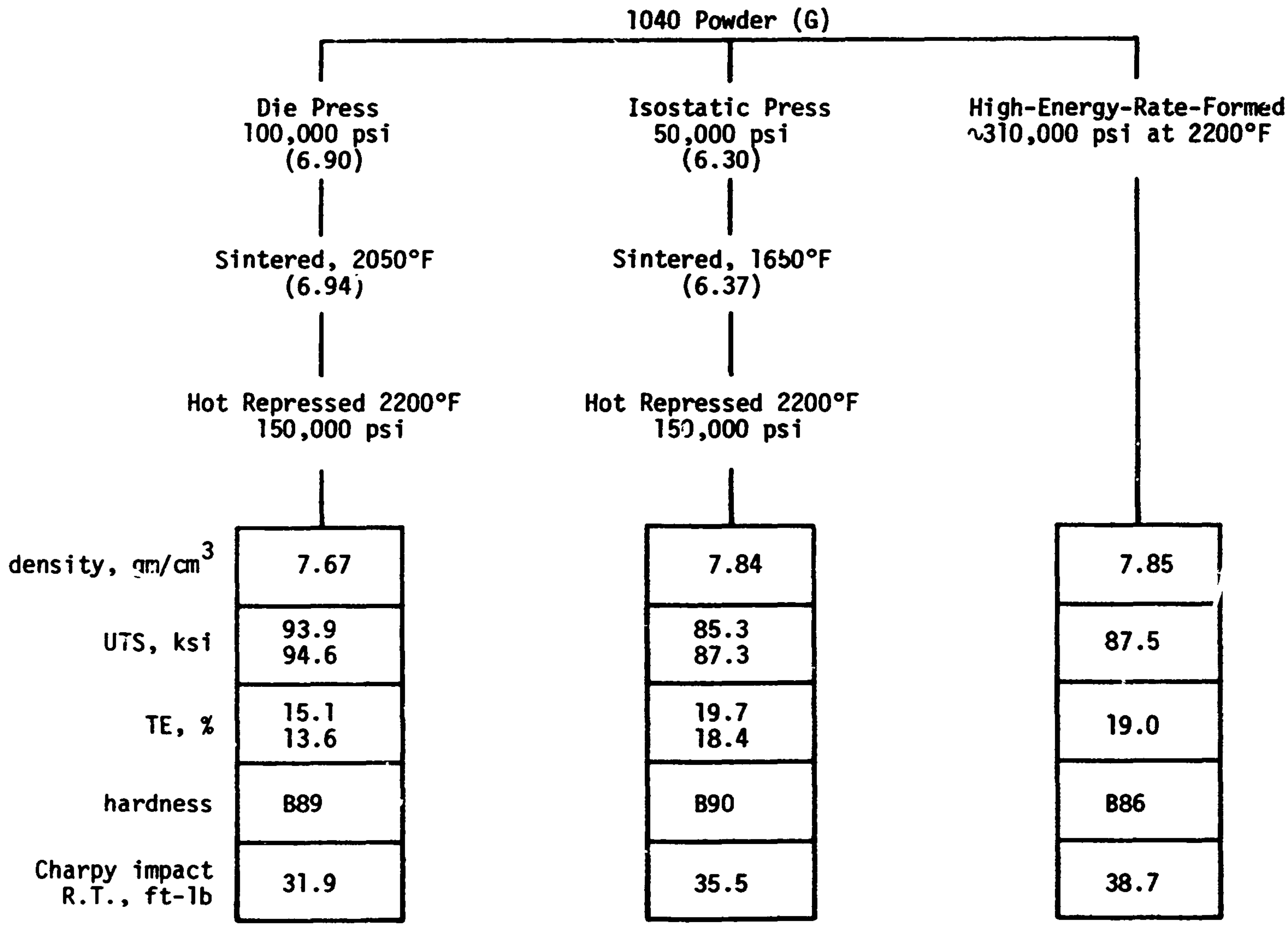


FIGURE 24. Cursory Study: Results of Best Processes, Hoeganaes Type 1040 Powder (G)

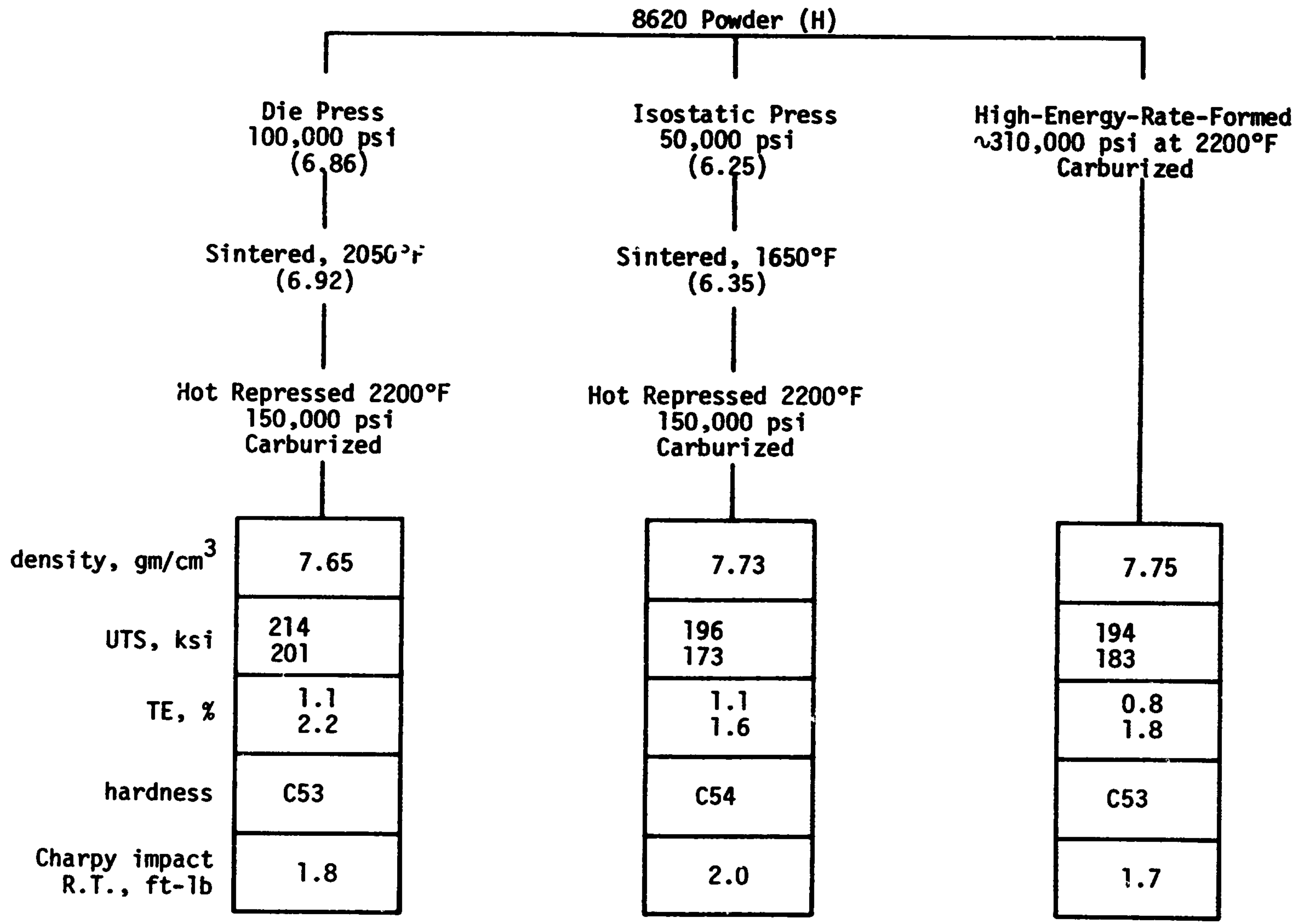


FIGURE 25. Cursory Study: Results of Best Processes, Hoeganaes Type 8620 Powder (H)

Type 1040 steel has a lower hardenability than any other material tested in the program, though it was considered adequate[27,28] for the through-hardening of the small forgings and 1/2 in. thick HERF slabs, all water quenched from the austenitizing temperature. A hardness of R_C 30 would be expected from a suitably transformed 1040 steel tempered at 900°F. The R_B readings of 86-90 and the UTS level of 85-90 ksi are typical of a normalized 1040 steel,[28] indicating insufficient hardenability in the P/M products to respond to a quench-temper operation. Products of this steel powder were the only ones tested which did not appear to center-harden.

The Task A processing of 1040 powder resulted in much poorer properties than those obtained from the best processes of the cursory study (compare Figures 16 and 24).

The properties of the 8620 powder (Lot H) are presented in Figure 25. The samples tested were all in the as-carburized and heat-treated condition, with a 15-mil case. A 450°F temper was used, instead of the standard 900°F temper.

This material exhibited the highest tensile strength of any steel used in the present study. It densified well, and of course had a very high apparent surface hardness, which is the hardness value given in the table. The apparent hardness of the material underlying the case would be much lower than the hardness values listed.

The Charpy V-notch values for powder Lots F, I, G, and H as a function of temperature are given in Table 2.

All impact strengths listed in Table 2 are of the same order of magnitude regardless of temperature or surface condition, with the exception of the high results of powder G. This is also the only material which indicates existence of a transition temperature.

TABLE 2

Charpy V-Notch Impact Properties of Specimens
Produced from Powder Lots F, G, H, and I by "Best Processes"

		Impact Energy, ft-lb			
	Powder	-40°F	77°F	210°F	450°F
Die Press	G	9.4	31.9	34.8	29.9
	I	2.6	2.5	3.2	1.9
	H	-	1.8	-	2.5
Isopress	G	14.4	35.5	26.8	32.0
	I	0.8	1.6	1.8	0.8
	H	-	2.0	-	1.7
HERF	F	1.6	1.5	1.5	1.3
	G	11.5	38.7	39.0	36.2
	I	1.4	1.0	1.0	1.1
	H	-	1.7	-	1.6

"Shelf Item" Powders

Five "shelf item" prealloyed powders, Lots J, K, L1, M, and N, were obtained from three major powder producers, and taken through the entire die press and sinter process already described in Figure 17 for the case of 4130 Lot B powder. Only the die press process was used as the initial compaction procedure on these powders. Charpy impact data was obtained as a function of temperature on specimens of each powder pressed at 80 ksi and sintered at 2050°F in the fashion of Task A processing.

Mechanical/physical property data for the shelf item powders may be found in Figures 26 through 30. Note that high temperature sintering followed by hot repressing produces the best properties. A large number of Lot J blanks and a few of Lot K did not survive the tensile specimen machining operation. Of the three 4650 type powders used in this portion of the program (J, K, and L1), Lot L1 exhibited superior densification, tensile strength, and elongation properties. It is interesting to note that initial compaction pressure had little if any effect on the properties of hot repressed material of these three powders; the subsequent sintering temperature appears to exert a much stronger influence.

50,000 psi Compacting Pressure (5.83)

Sinter 1650°F

	Cold Repress & Sinter	Sinter 1650°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.27 6.40	5.78	7.59	7.67
UTS, ksi	60.0 66.3	c	96.0 89.0	157[d] 176
TE, %	0.7 0.5	---	0.9 0.3	1.0 0.6
hardness	B86	B80	C43	C39

Sinter 2050°F

	Cold Repress & Sinter	Sinter 2050°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.27 6.31	5.95	7.69	7.72
UTS, ksi	50.0 52.0	c	193 145	137 184
TE, %	0.5 0.4	---	2.0 0.5	2.2 2.4
hardness	B87	B78	C41	C39

80,000 psi Compacting Pressure (6.18)

Sinter 1650°F

	Cold Repress & Sinter	Sinter 1650°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.39 6.52	6.13	7.53	7.61
UTS, ksi	57.8 64.7	c	94.0 89.0	c
TE, %	0.3 0.4	---	0.4 0.3	---
hardness	B90	B85	C42	C43

Sinter 2050°F

	Cold Repress & Sinter	Sinter 2050°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.43 6.52	6.31	7.63	7.66
UTS, ksi	65.0 64.0	39.0 41.0	162 168	146 177
TE, %	0.5 0.4	0.5 0.3	1.3 0.5	1.2 1.0
hardness	B92	B91	C39	C38

100,000 psi Compacting Pressure (6.33)

Sinter 1650°F

	Cold Repress & Sinter	Sinter 1650°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.55 6.68	6.38	7.60	7.59
UTS, ksi	67.5 65.7	c	87.8[b]	c
TE, %	1.0 0.3	---	0.7	---
hardness	B96	B88	C43	C39

Sinter 2050°F

	Cold Repress & Sinter	Sinter 2050°F	Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.64 6.70	6.59	7.65	7.73
UTS, ksi	66.3 72.0	59.0 55.3	158 177	150 197
TE, %	0.7 0.4	0.4 0.3	1.7 1.1	1.2 0.5
hardness	B96	B92	C38	C41

b - One sample broke during machining.
c - Two samples broke during machining.
d - Sample broke at head.

FIGURE 26. Task B: Results of Die Press Processing of Glidden-Durkee Type 4650 Powder (J)

50,000 psi Compacting Pressure (6.10)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.71/6.82	6.03	7.60	7.70	6.36/6.44	6.17	7.64	7.67
UTS, kwi	76.0 76.1	c	c	152[d] 183	62.0 58.5	32.0[b]	188 189	160 178
TE, %	0.4 0.3	---	---	0.6 2.1	0.3 0.3	0.3	1.9 2.6	1.1 2.3
hardness	B91	B56	C39	C39	B86	B81	C39	C38

80,000 psi Compacting Pressure (6.58)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.80/6.96	6.48	7.61	7.64	6.73/6.82	6.65	7.67	7.68
UTS, ksi	87.0[b]	8.0[d,b]	155 163	150[b]	78.0 91.9	68.5 69.7	180 87.0	178 172
TE, %	0.4	0.2	0.6 2.3	0.8	0.5 0.4	0.5 0.4	1.3 0.4	2.1 0.9
hardness	C24	B62	C39	C40	B97	B93	C38	C38

100,000 psi Compacting Pressure (6.79)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	6.98/7.08	6.69	7.64	7.62	6.90/6.98	6.85	7.66	7.67
UTS, ksi	101 41.6	15.8[d,b]	128[b]	142 153	90.0 105	69.0 63.8	171 177	175 175
TE, %	0.5 1.0	0.2	0.6	1.2 1.6	0.6 1.0	0.3 0.3	0.7 2.0	.1 2.0
hardness	C26	B79	C35	C41	C23	B94	C40	C39

b - One sample broke during machining.
c - Two samples broke during machining.
d - Sample broke at shoulder.

FIGURE 27. Task B: Results of Die Press Processing of Glidden - Durkee Type 4600 + 0.5 C Powder (K)

50,000 psi Compacting Pressure (6.46)

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm^3	7.01 7.05	6.45	7.70	7.65	6.60 6.56	6.43	7.84	7.72
UTS, ksi	127 112	33.8 36.5	143 159	177 177	87.8 88.0	77.5 75.8	182 180	178 174
TE, %	1.4 1.2	0.4 0.2	3.1 2.8	4.9 4.8	0.6 0.2	0.6 0.2	5.2 6.5	5.8 6.0
hardness	B99	B43	C30	C36	B83	B89	C37	C36

80,000 psi Compacting Pressure (6.89)

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm^3	7.22 7.33	6.91	7.77	7.60	6.99 7.00	6.93	7.80	7.77
UTS, ksi	150 145	97.0 83.0	125 151	152 184	128 120	107 116	188 184	185 180
TE, %	1.7 2.2	1.0 1.5	3.2 3.2	0.7 5.1	0.7 1.3	0.4 1.0	5.9 6.2	6.2 5.9
hardness	C24	B54	C26	C36	C20	B98	C38	C35

100,000 psi Compacting Pressure (7.11)

	Sinter 1650°F: Cold Repress & Sinter	Sinter 1650°F	Sinter 1650°F: Hot Repress 1800°F	Sinter 1650°F: Hot Repress 2200°F	Sinter 2050°F: Cold Repress & Sinter	Sinter 2050°F	Sinter 2050°F: Hot Repress 1800°F	Sinter 2050°F: Hot Repress 2200°F
density, gm/cm^3	7.34 7.38	7.08	7.76	7.67	7.19 7.19	7.15	7.81	7.72
UTS, ksi	157 152	35.0 36.0	160 158	185 180	138 133	137 132	189 185	184 181
TE, %	2.3 2.0	1.0 1.4	2.6 3.6	4.0 3.4	1.5 1.8	1.2 1.2	3.6 6.2	4.3 6.6
hardness	C28	B58	C32	C37	C21	C21	C38	C34

FIGURE 28. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 4600 + 0.5 C Powder (L1)

50,000 psi Compacting Pressure (6.31)

Sinter 1650°F		Sinter 1650°F	Sinter 1650°F		Sinter 2050°F		Sinter 2050°F	Sinter 2050°F
Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F		Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
6.99 6.93	6.30	7.64	7.82	density, gm/cm^3	6.81 6.88	6.32	7.68	7.83
89.3 89.9	23.9[b]	62.3 62.0	157 170	UTS, ksi	89.5 91.6	40.2 46.0	166 168	163 167
1.2 1.1	0.2	1.8 1.4	0.7 4.2	TE, %	0.8 1.4	0.3 0.6	3.4 2.5	4.8 5.0
B91	B13	B86	C37	hardness	B92	B72	C34	C32

80,000 psi Compacting Pressure (6.81)

Sinter 1650°F		Sinter 1650°F	Sinter 1650°F		Sinter 2050°F		Sinter 2050°F	Sinter 2050°F
Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F		Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
7.09 7.09	6.77	7.74	7.70	density, gm/cm^3	7.03 7.06	6.81	7.83	7.83
106 108	13.5 19.7	64.0 59.6	173 124	UTS, ksi	96.0 103	81.0 75.8	173 171	166 165
0.5 2.6	0.2 0.3	2.2 0.9	1.1 1.1	TE, %	0.6 1.6	0.4 1.4	2.4 3.8	4.2 5.0
B96	B31	B89	C36	hardness	B91	B88	C34	C35

100,000 psi Compacting Pressure (7.01)

Sinter 1650°F		Sinter 1650°F	Sinter 1650°F		Sinter 2050°F		Sinter 2050°F	Sinter 2050°F
Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F		Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
7.29 7.20	6.97	7.68	7.90	density, gm/cm^3	7.14 7.16	7.00	7.80	7.81
104 111	88.5[b]	68.5 68.6	160 161	UTS, ksi	107 103	86.0[b]	158 159	155 156
0.7 1.6	0.7	2.1 1.4	3.8 2.6	TE, %	0.9 1.0	0.5	2.8 3.9	3.7 5.0
B96	B95	B89	C35	hardness	B98	B89	C32	C33

b - One sample broke during machining

FIGURE 29. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 8600 + 0.5 C Powder (M)

50,000 psi Compacting Pressure (6.33)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	7.06 / 7.01	6.35	7.64	7.72	6.87 / 6.87	6.30	7.63	7.72
UTS, ksi	93.5 93.0	22.4 20.2	80.6 82.0	145 133	77.0 74.4	46.8 47.0	172 140	166 153
TE, %	0.8 2.0	1.5 1.1	7.4 7.5	6.5 7.6	0.9 1.6	0.6 1.0	4.2 5.0	5.7 6.2
hardness	B93	B5	B88	C30	B78	B70	C31	C32

80,000 psi Compacting Pressure (6.86)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	7.20 / 7.18	6.86	7.70	7.71	7.07 / 7.05	6.85	7.77	7.83
UTS, ksi	103 93.3	75.8 29.4	76.5 84.8	130 127	86.0 87.2	66.0 65.4	128 133	145 146
TE, %	1.4 1.6	3.8 2.6	7.0 7.8	7.3 7.5	0.2 1.6	0.6 1.0	3.5 7.6	6.1 6.4
hardness	B96	B26	B85	C30	B91	B80	C30	C30

100,000 psi Compacting Pressure (7.05)

	Sinter 1650°F				Sinter 2050°F			
	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F	Cold Repress & Sinter		Hot Repress 1800°F	Hot Repress 2200°F
density, gm/cm^3	7.25 / 7.23	7.03	7.70	7.75	7.16 / 7.17	7.01	7.80	7.86
UTS, ksi	102 109	32.5 33.3	80.3 87.3	134 132	95.5 94.9	78.0 78.1	142 137	135 138
TE, %	1.3 1.7	2.2 2.4	7.4 8.0	6.3 7.0	0.9 2.2	0.8 0.8	5.5 4.3	7.9 7.8
hardness	B91	B40	B87	C30	B96	B83	C30	C30

FIGURE 30. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 9400 + 0.5 C Powder (N)

Metallography of pressed-and-sintered and hot repressed samples of the five shelf item powders are shown in Figures 31 and 32.

Yield data may be found in the section appended to this report. Yield data were not obtained on some samples of J and K materials because of erratic extensometer behavior. The impact properties of the shelf item powders are presented in Table 3.

TABLE 3

Charpy V-Notch Impact Properties of Specimens Produced from Powder Lots J, K, L1, M, and N Compacted 80 ksi, Sintered 2050°F, Tempered 900°F

	Impact Energy, ft-lb			
Powder	-40°F	77°F	210°F	450°F
J	1.1	0.9	0.8	0.8
K	1.0	1.0	0.9	0.8
L	1.4	1.4	1.4	1.3
M	1.2	1.2	1.3	1.4
N	1.2	1.5	1.5	1.3

Impact properties are low, with no apparent temperature effect. The data of Table 3 shows a slight superiority of Lot L1 over Lots J and K.

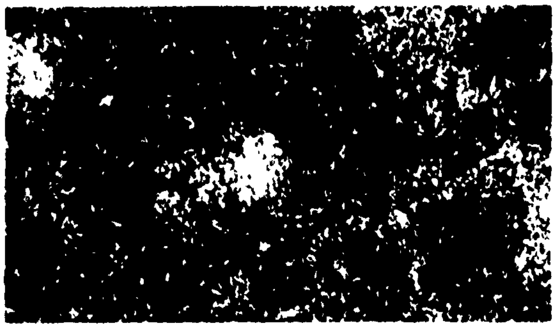
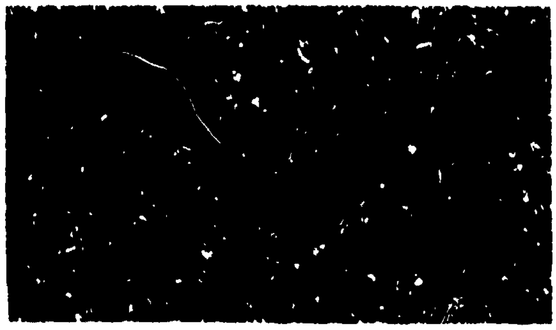
Task B Data Summary

In this concluding portion of the Task B Discussion Section, data obtained from the six powders taken through the extensive die press and sinter process sequence are graphically presented to permit a better understanding and comparison of their various properties.

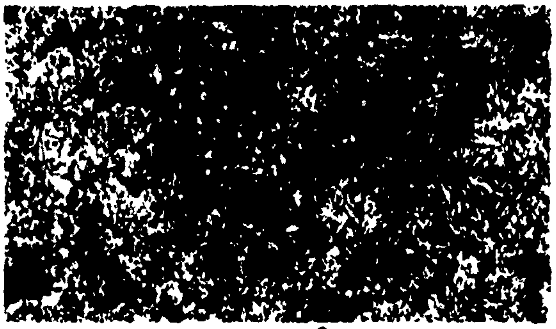
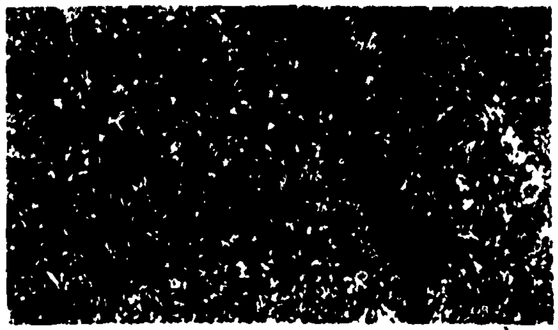
The effect of compacting pressure and compacting pressure plus sintering on density of the resulting product is shown in Figures 33 and 34, respectively. Powder Lot L1 yields compacts of the highest density, while the carbon-alloyed powders, Lots B and J, yield compacts of the lowest density.

Samples Pressed 100 KSI
Sintered 2050 °F
Austenitized, Quenched
Tempered 900 °F

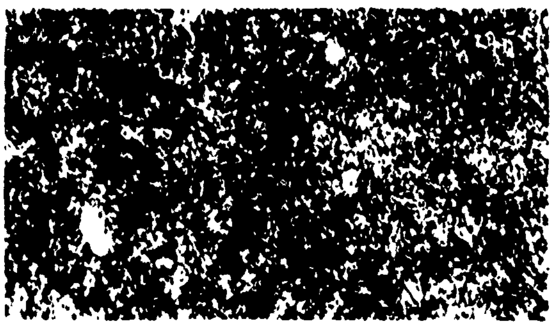
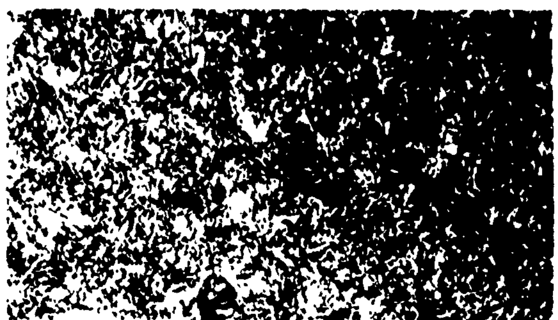
Samples Pressed 100 KSI
Sintered 2050 °F
Hot Repressed 2200 °F at 150 KSI
Austenitized, Quenched
Tempered 900 °F

Density 6.59 gm/cm^3 4650 (J) Density 7.73 gm/cm^3

Density 6.85 gm/cm^3 4600 + 0.5C (K) Density 7.67 gm/cm^3

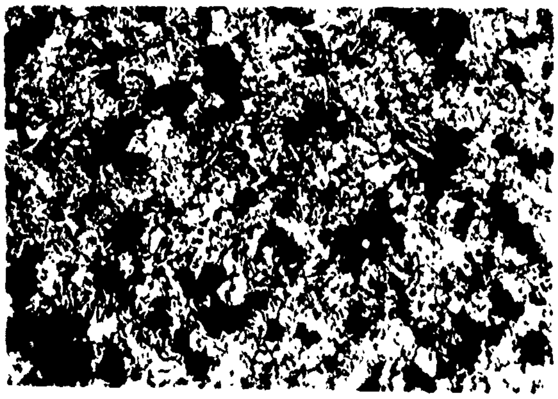



Density 7.15 gm/cm^3 4600 + 0.5C (L1) Density 7.72 gm/cm^3

FIGURE 31. Microstructures of Pressed-and-Sintered and Hot Repressed Samples 250X

Samples Pressed 100 KSI
Sintered 2050 °F
Austenitized, Quenched
Tempered 900 °F

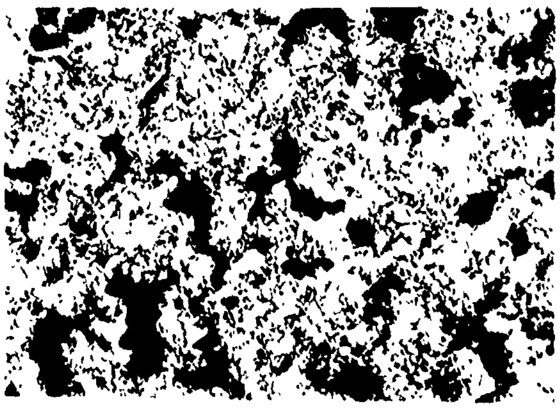
Samples Pressed 100 KSI
Sintered 2050 °F
Hot Repressed 2200 °F at 150 KSI
Austenitized, Quenched
Tempered 900 °F



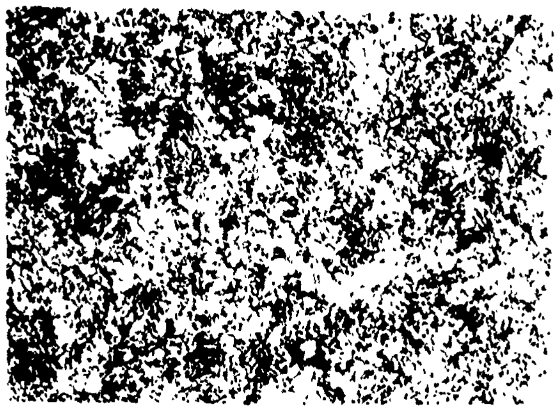
Density 7.00 gm/cm^3

Density 7.81 gm/cm^3

8600 + 0.5C (M)



Density 7.01 gm/cm^3



Density 7.86 gm/cm^3

9400 + 0.5C (N)

FIGURE 32. Microstructures of Pressed-and-Sintered and Hot Repressed Samples 250X

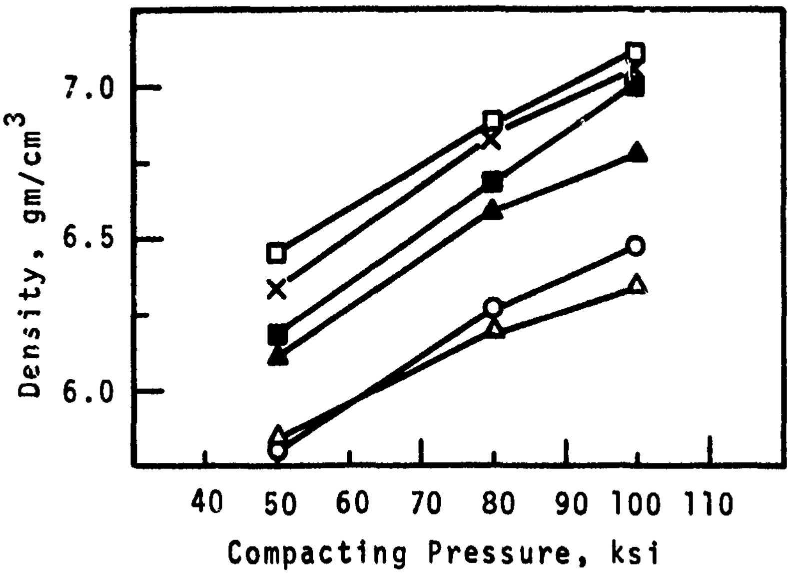


FIGURE 33. Effect of Compacting Pressure on Density

Legend

○ 4130, Lot 1 Hoeganaes (B1)

△ 4650, Glidden (J)

▲ 4600 + 0.5 C Glidden (K)

□ 4600 + 0.5 C A. O. Smith (L1)

■ 8600 + 0.5 C A. O. Smith (M)

× 9400 + 0.5 C A. O. Smith (N)

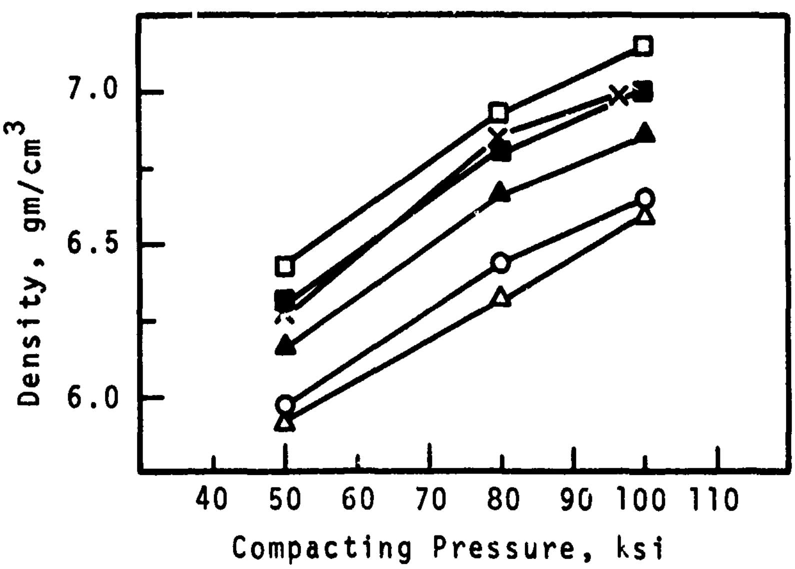


FIGURE 34. Combined Effect of Compacting Pressure and 2050°F Sinter on Density

The effect of compaction followed by a repress and a resinter on density is shown in Figure 35. The beneficial effect of high initial compacting pressure on ultimate density is still apparent. Initial compaction pressure becomes a variable of minor importance, however, when the process culminates in a hot repress operation (Figure 36).

The relationship between the hardness and the ultimate tensile strength of the die-press produced compacts is shown in Figure 37. Only samples with hardnesses >R_C 20 were plotted on this figure.

With the exception of some low values, notably data points associated with powder Lots B and J (the totally prealloyed materials), there is a good agreement between apparent product hardness and UTS of the P/M products with published data for wrought steels. Steel powders producing compacts of high density, such as Lot L1, are found above the wrought-product line; low density materials, such as Lots B and J, are found below. The relationship between UTS and density is explored further in Figure 38. Materials in the top part of the scatter band, such as Lot L1 at a density of 7.7 gm/cm^3, have a high strength/density ratio; materials in the bottom (e.g., Lot K at a density of 6.9 gm/cm^3) are relatively inefficient.

6.3 <u>Task C</u>

Task C was a hot repressing study, in which repressing pressure and temperature were varied over a wide range, and the effect of this variance on the mechanical properties of the resulting test pieces determined. The hot repressing fabrication mode was emphasized because it is recognized that optimum P/M properties will eventually be routinely obtained by some preform forging process. While the hot repressing operation utilized here does not produce the optimum mechanical properties (notably impact strength) which can be obtained by forging processes which involve extensive lateral metal flow (see Section 5.6, <u>Hot Repressing</u>), the study shows relative behavior of materials, relative response to repressing variables, and properties obtainable from commercial powders by state-of-the-art repressing operations without emphasizing preform design.

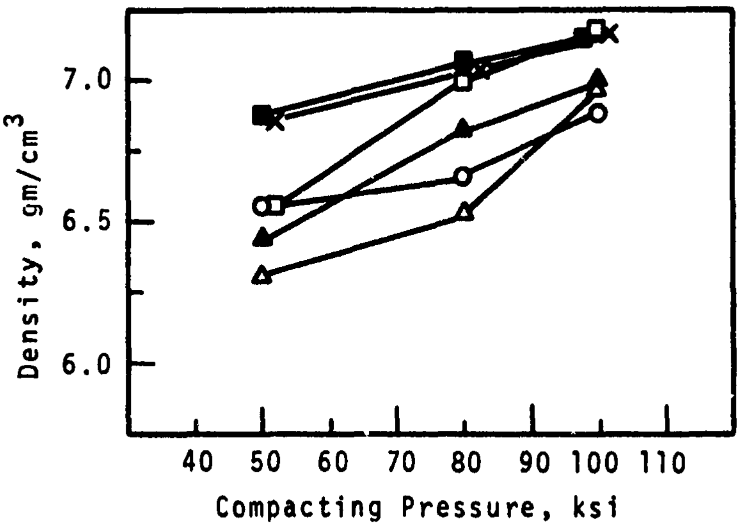


FIGURE 35. Combined Effect of Compacting Pressure 2050°F Sinter, Cold Repress,(a) and Resinter(b) on Density

Legend

- ○ 4130, Lot 1 Hoeganaes (B1)
- △ 4650, Glidden (J)
- ▲ 4600 + 0.5 C Glidden (K)
- □ 4600 + 0.5 C A. O. Smith (L1)
- ■ 8600 + 0.5 C A. O. Smith (M)
- × 9400 + 0.5 C A. O. Smith (N)

a - 80 ksi, R.T.
b - 2050 °F
c - 150 ksi

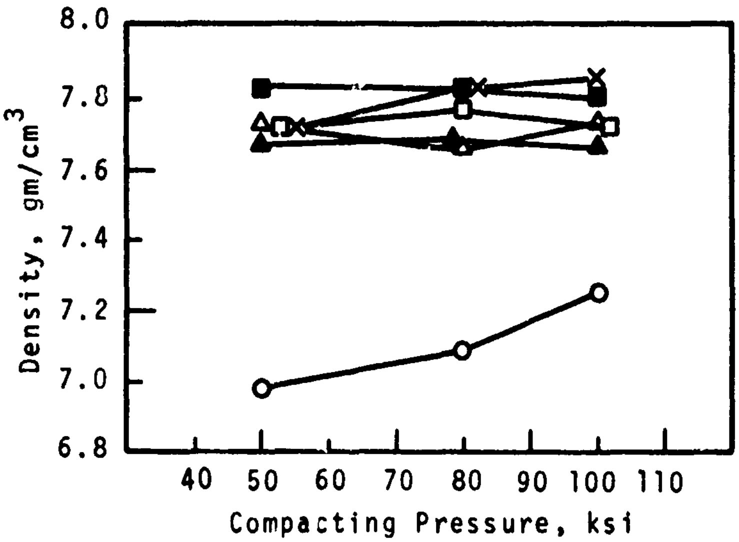


FIGURE 36. Combined Effect of Compacting Pressure, 2050°F Sinter, and 2200°F Hot Repress (c) on Density

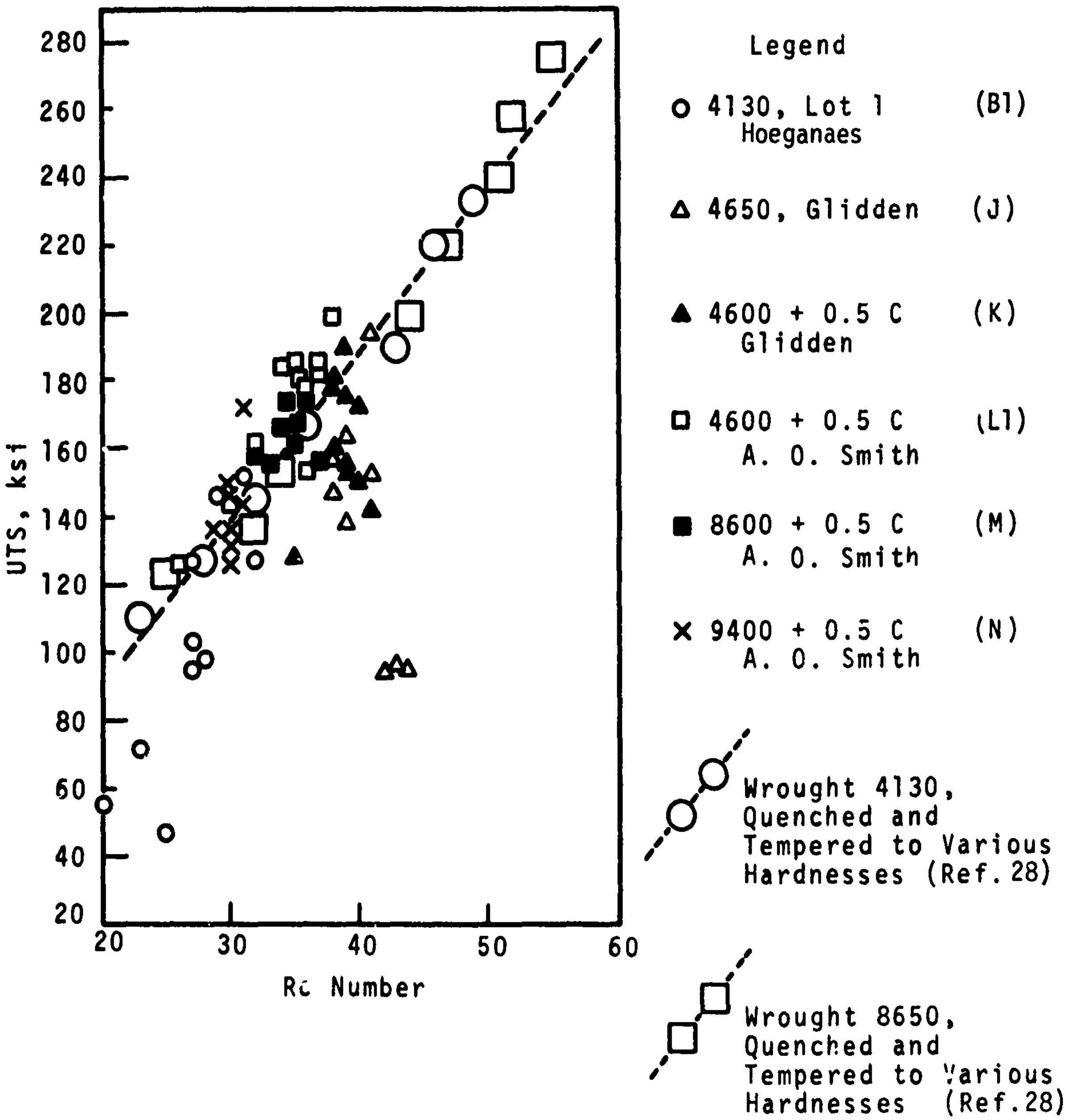


FIGURE 37. Relationship Between Ultimate Tensile Strength and Rockwell C Hardness Number (For Die Press Processed Samples with Hardnesses >Rc 20)

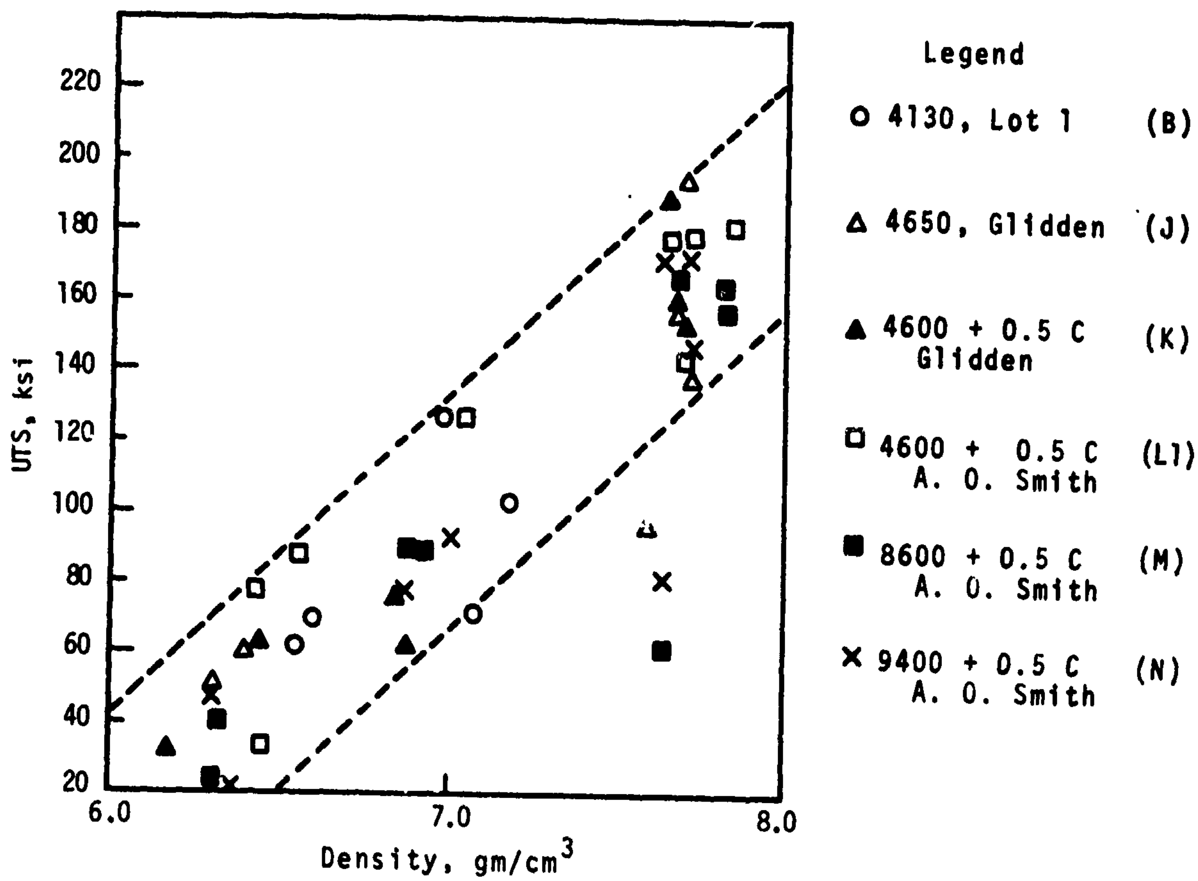


FIGURE 38. Relationship Between Ultimate Tensile Strength and Density (For Die Press Processed Samples Compacted Initially at 50 ksi)

Four prealloyed steel powders were selected for the Task C hot repressing study:

- 4130, Hoeganaes (B2)
- 4600 + 0.4 C, A. O. Smith-Inland (L2)
- 4650, Glidden-Durkee (J)
- 8620, Hoeganaes (H)

All powders are described in detail in the section of the report entitled MATERIALS.

Three repressing pressures were used: 80 ksi, 120 ksi, and 160 ksi; and three forging temperatures: 1800°F, 2000°F, and 2200°F.

All preforms were formed by cold compaction at 100,000 psi, followed by a 2050°F sinter. The preforms so produced varied widely in density before the hot repress operation. This variation is shown in Table 4.

TABLE 4

Density of Preforms After Compaction (100 ksi) and Sinter (2050°F)

Material	Preform Density, gm/cm^3	
	After Compaction	After Sinter
4130 (B2)	6.86	6.92
4600 + 0.4 C (L2)	7.20	7.21
4650 (J)	6.50	6.60
8620 (H)	6.97	7.05

The preforms were brought to temperature in a flowing argon atmosphere prior to repressing. They were rapidly transferred to the repressing dies (<5 seconds transfer time), and pressed. The dies were preheated to 800°F.

After repressing, the bars of B2, L2, and J were austenitized at 1575°F in endothermic gas, water quenched, tempered at either 900°F or 1100°F, and machined into test specimens. The bars of 8620 (H) were machined to shape, pack carburized to yield a case approximately 15-mil

thick (see Section 5.8, Heat Treating and Carburizing), austenitized at 1575°F, water quenched, then tempered at either 900°F or 450°F.

All bars of J material showed some degree of cracking after the water quench (see Figure 39). Most cracks were confined to the surface, and so generally did not affect the final test piece. No other material was susceptible to cracking.

The effect of pressure and temperature on sample density is shown in Figure 40. Powder L2, 4600 + 0.4 C, densifies far more easily than the other powders tested, and is influenced relatively little by repress temperature. The densification of powder J, a completely prealloyed 4650 which is relatively difficult to press, was significantly aided by increased repress temperature.

The hardness of the final samples as a function of repress temperature and pressure is shown in Figure 41. The 8620 material (H) was carburized prior to taking hardness measurements, hence the high values for that material. On the whole, the hardness is relatively insensitive to the density changes induced by the repressing parameters employed.

The absolute values of hardness found in Task C work were somewhat less than those obtained in Task B for equivalent materials heat treated in seemingly identical fashion. For example, bars of J material fabricated for Task B studies exhibited hardness values in the range C38 to C43 after a 900°F temper; J material in Task C varied from C34 to C39 after the same heat treatment. Other materials show a similar decrease in hardness. The exact reason for the lower hardness values is not known. It is possible that slight differences in endothermic gas composition during the austenitizing treatment may have resulted in lower carbon levels, hence lower hardness values, in the Task C samples.

The relationship between ultimate tensile strength and repressing parameters is shown in Figure 42. The average elongation of the samples represented by each curve is also noted in the figure. The data of this figure are derived from the single samples yielding the highest UTS of the duplicate samples of each material tested. Note that the UTS is almost

FIGURE 39. Bars of 4650 (J) Material After Quench

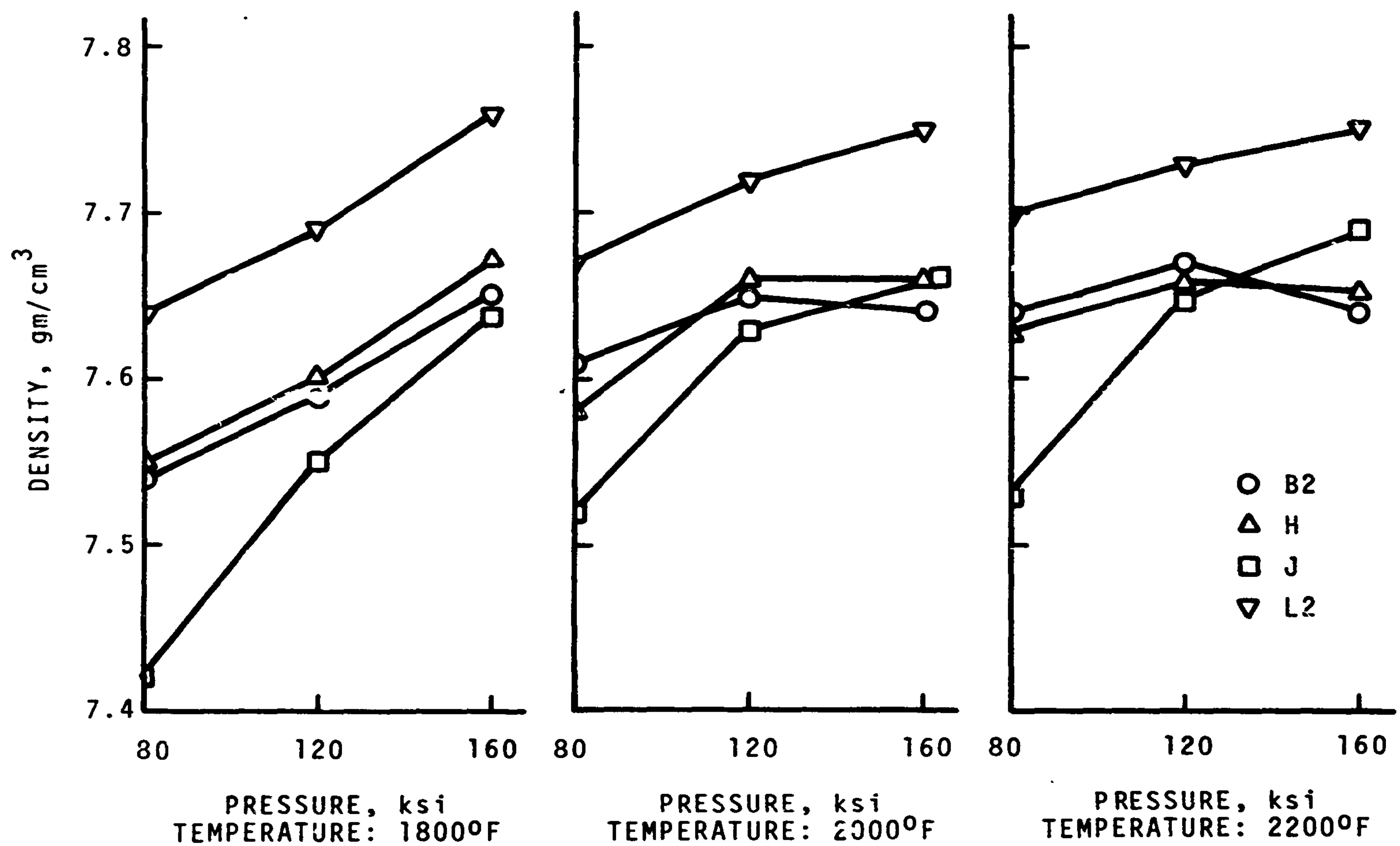


FIGURE 40. Effect of Hot Repress Pressure and Temperature on Density All samples cold pressed 100 ksi, sintered 2050°F prior to forging.

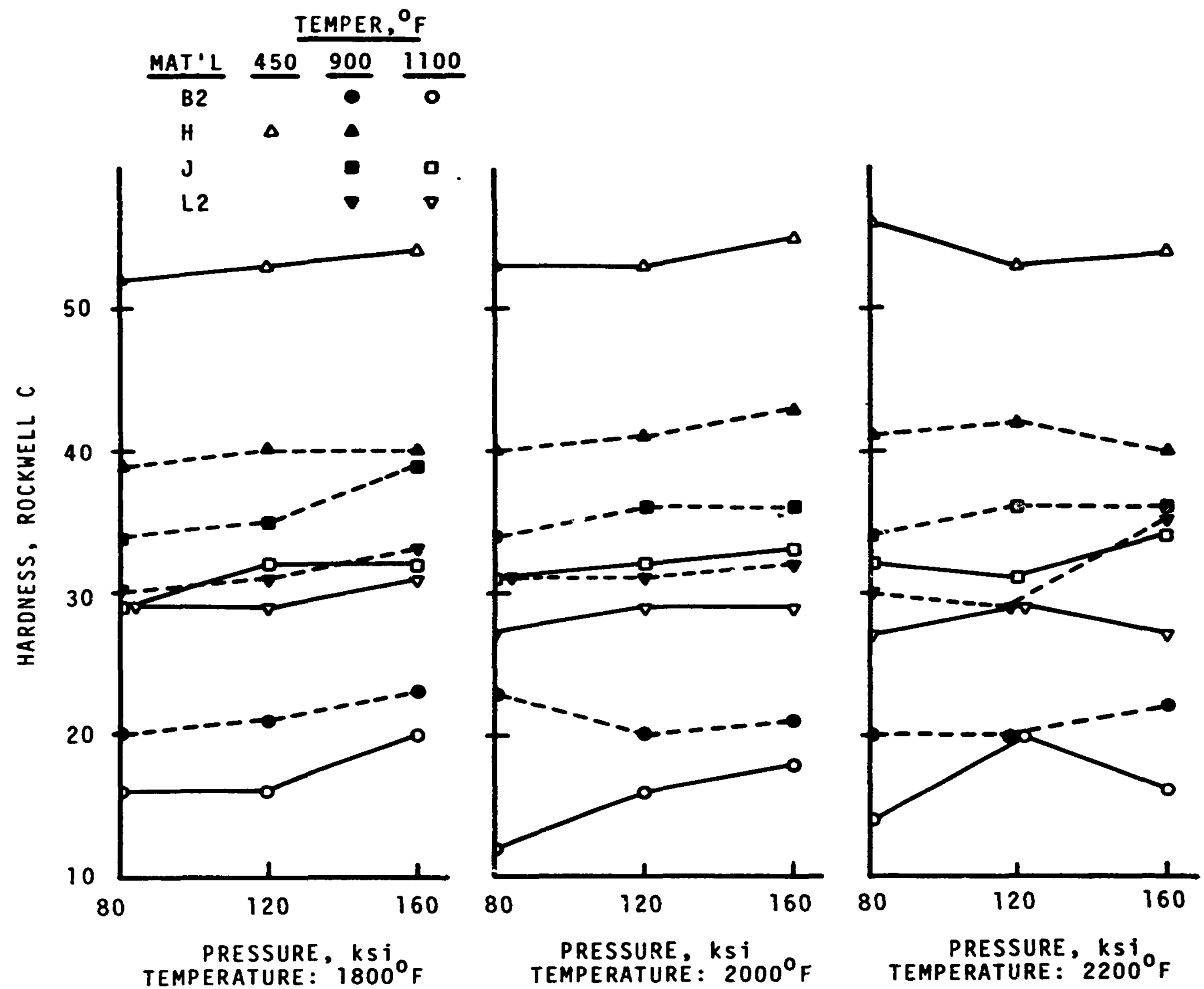


FIGURE 41. Effect of Hot Repress Pressure and Temperature on Hardness of Final Heat-Treated Samples

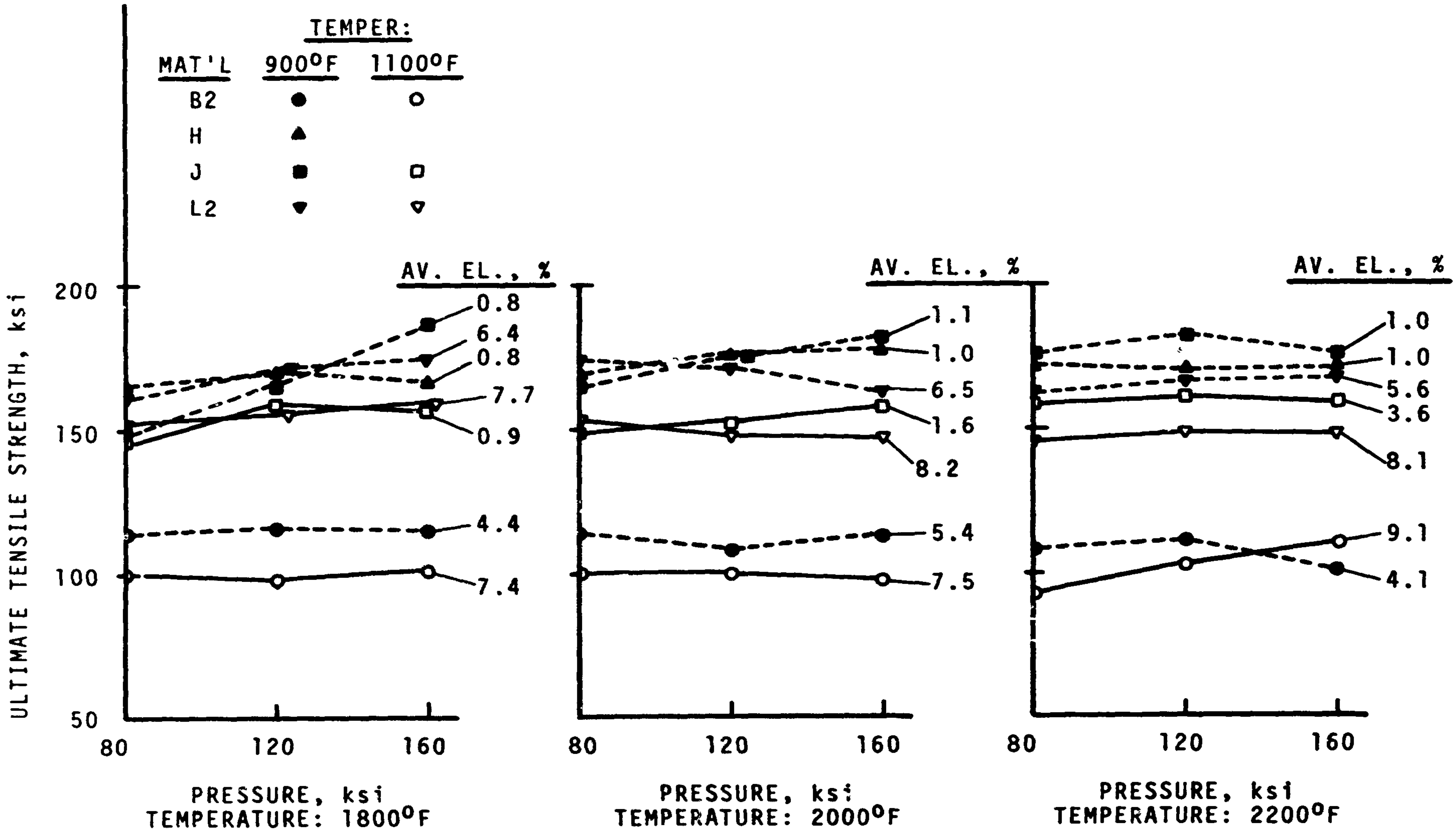


FIGURE 42. Effect of Hot Repress Pressure and Temperature on Ultimate Tensile Strength

independent of repressing parameters over the range of pressure and temperature chosen for study. The UTS values compare favorably with those of wrought materials at the same hardness levels. The elongation values, however, are much lower than those expected for wrought materials.

Elongation data are presented for the individual Task C samples in the appendix, along with the detailed YS and UTS data.

The relationship between impact properties and repressing parameters is shown in Figure 43. All of the impact property values are low and relatively independent of repressing pressure and temperature, with the exception of the 4600 + 0.4 C (L2) samples, which show a decided improvement in properties with increasing temperature and pressure. The data of Figure 43 represent the single samples yielding the highest impact energy absorption of the duplicate samples tested. Detailed impact data are presented in the appendix.

Some representative microstructures of the Task C materials are shown in Figures 44 and 45. Note that the carburized case on the less dense samples of 8620 (H) extends considerably deeper than the approximate 15-mil case depth found on dense samples (Figure 45).

It appears likely that the low tensile elongation and low impact strength values generally found in the present work (Task B as well as Task C) can be related to two major factors: possible internal oxidation of the sample during the preform preheat and subsequent transfer to the repress dies, and lack of substantial transverse metal flow during the repress operation. No effort was made in the present study to inhibit oxidation of the preform during the transfer operation, and significant internal oxidation could have taken place, which would tend to embrittle the material.[5] Transverse metal flow was not permitted by die design, so that very high densities could not be generally obtained. Such metal flow would also be expected to assist in breaking up internal oxide films, so that some of the inherent qualities of the material could be recovered.

The 4600 + 0.4 C (L2) material which formed the densest preform also yielded the best impact properties and generally the best elongation

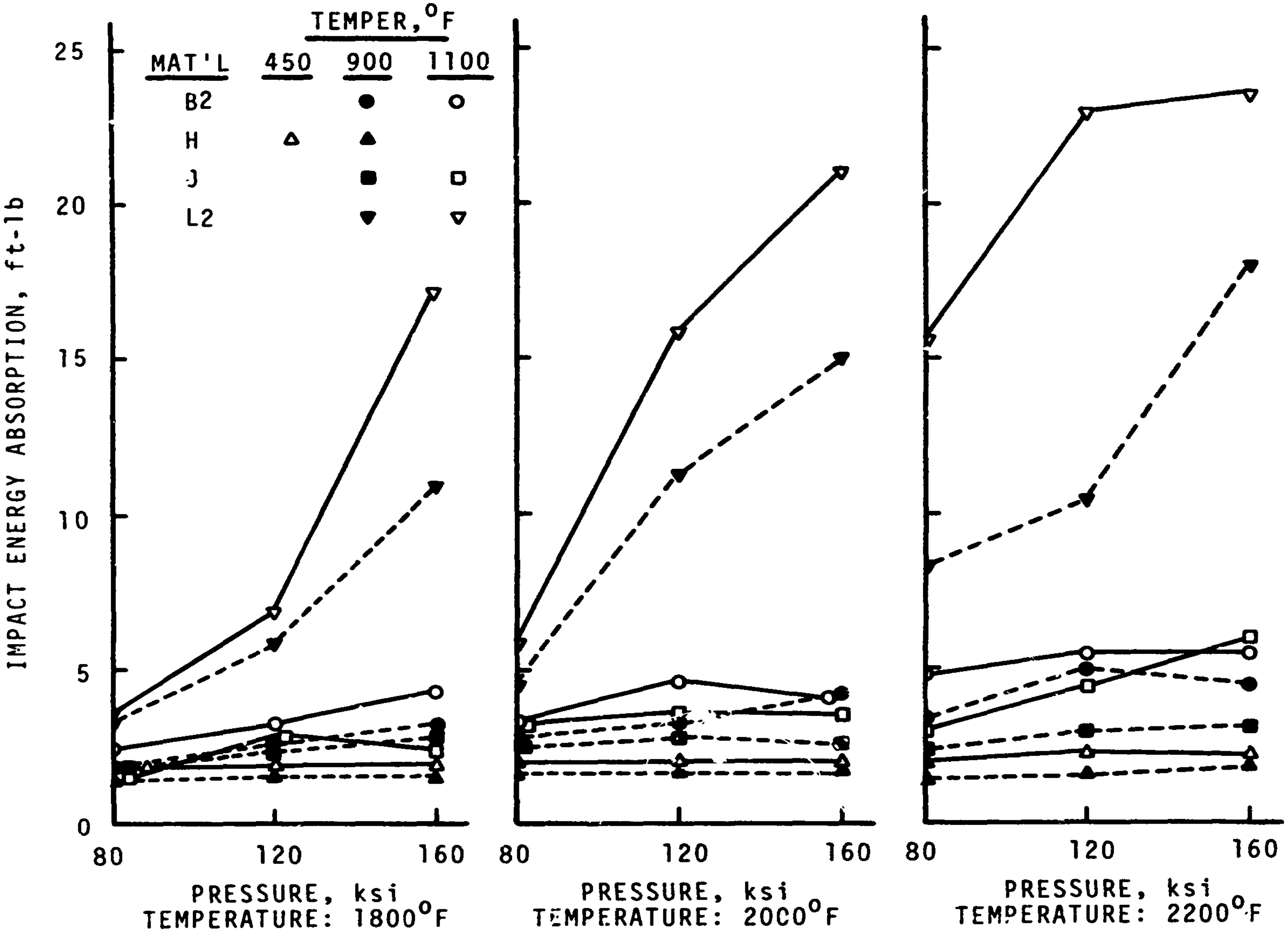
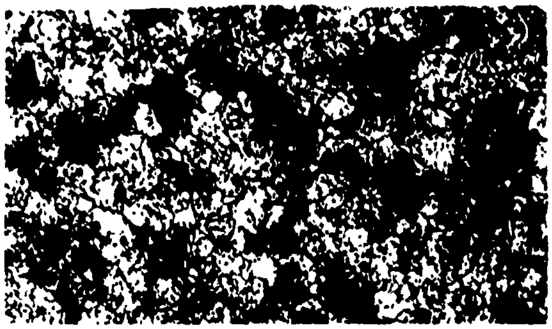


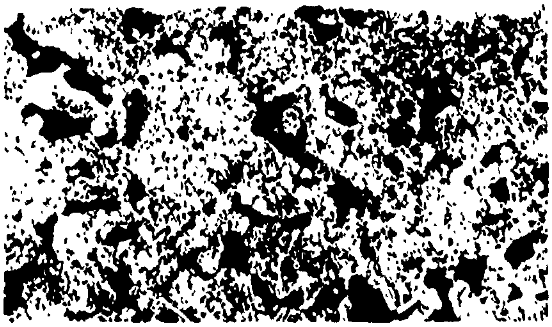
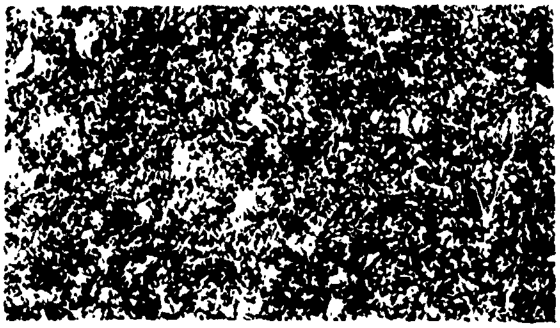
FIGURE 43. Effect of Hot Repress Pressure and Temperature on Room Temperature Impact Properties

Samples Pressed 100 ksi
Sintered 2050 °F
Austenitized, Quenched
Tempered 900 °F

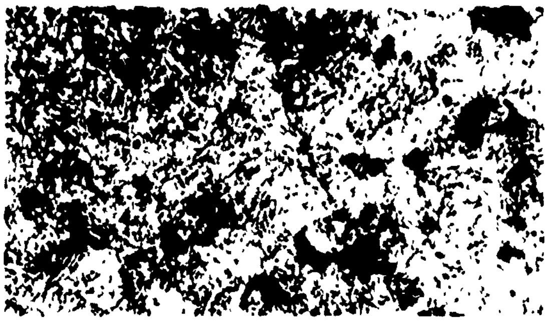
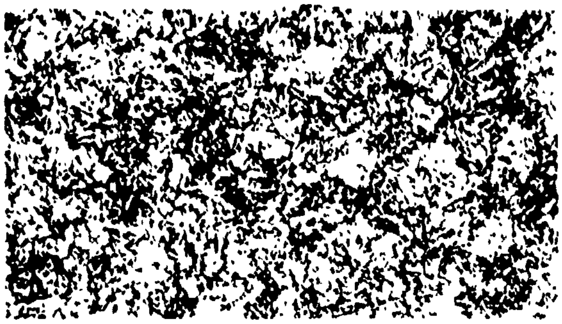
Samples Pressed 100 ksi
Sintered 2050 °F
Hot Repressed 2200 °F, 160 ksi
Austenitized, Quenched
Tempered 900 °F




Density 6.92 gm/cm^3 4130 (B2) Density 7.64 gm/cm^3

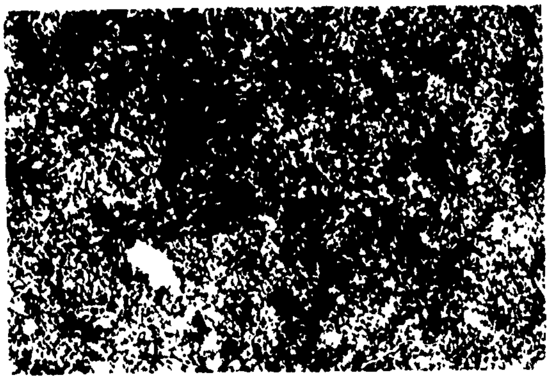
Density 6.60 gm/cm^3 4650 (J) Density 7.69 gm/cm^3

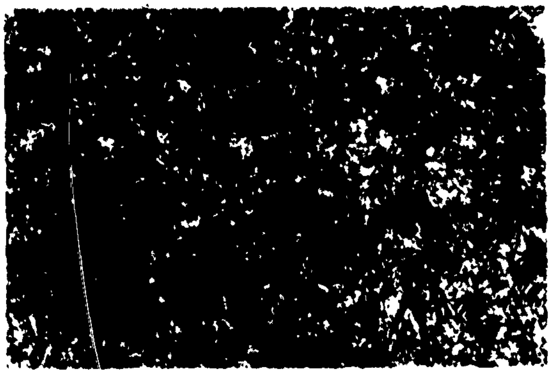
Density 7.21 gm/cm^3 4600 + 0.4C (L2) Density 7.75 gm/cm^3

FIGURE 44. Microstructures of Pressed-and-Sintered and Hot Repressed Samples 250X

Sample Pressed 100 ksi Sintered 2050 °F Pack Carburized 1700 °F, 2 hr Austenitized, Quenched Tempered 900 °F	Sample Pressed 100 ksi Sintered 2050 °F Hot Repressed 2200 °F, 160 ksi Pack Carburized 1700 °F, 2 hr Austenitized, Quenched Tempered 900 °F

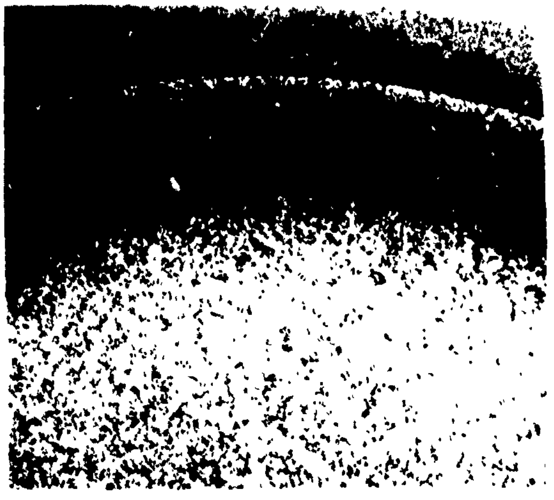


Sample Center 250X



Sample Center 250X

Sample Surface 40X



Sample Surface 40X

FIGURE 45. Microstructures of Pressed-and-Sintered and Hot Repressed Samples of Carburized 8620(H) Material

properties of the materials studied. The denseness of the preform, coupled with the chromium-free steel composition and the graphite admix could have significantly inhibited internal oxidation of this material relative to the other materials. The carburized material (H) exhibited the poorest elongation and impact properties of any of the materials tested.

There was no effort made to quantify the relative contributions of the various factors suspected of contributing to the general lack of elongation and impact strength of the materials studies, as such investigations were beyond the scope of the present program. The results obtained, however, illustrate the necessity of preform design to insure adequate metal flow, oxidation protection of the preform during preheat and transfer operations, and careful investigatory work during formulation of any preform forging procedure to detect and eliminate any factors which might contribute to undue property degradation.

It is interesting to compare mechanical property values obtained in the present work with those obtained by other investigators. It is generally difficult to make direct comparisons, because of the wide variety of materials, fabrication processes, heat treatments and testing procedures employed by various investigators. It is possible, however, to make a fairly meaningful comparison between the mechanical property values obtained by several investigators on forged, heat treated 4600 + 0.4 - 0.5 C steel bars. This comparison is made in Table 5. The 4600 prealloyed powder is A. O. Smith water atomized material in all cases. Forging procedures differed substantially, however.

The properties reported actually show fairly good agreement, in spite of the wide variation in forging procedures employed. Unfortunately, impact data, one of the most sensitive indicators of sample quality, is not available in all cases.

By way of comparison, wrought 4640 material is expected to exhibit a Charpy impact value of 39 ft-lbs, an elongation of 12.0 percent, and an ultimate strength of 182,200 lb/in.^{2} at a hardness of C36 (800°F temper).(17)

TABLE 5

Comparison of Mechanical Properties of 4600 + 0.4 - 0.5 C Material Fabricated by Different Investigators

C	Density % Th.	Temper, °F	Rockwell Hardness	UTS, ksi	El., %	Charpy V-Notch, ft-lb	Reference
0.41	>98	800	C35	185.4	6.8	9.5	17
0.46	98.6	1100	C34-33	152.2	13	-	10
0.40	99.89	1050	-	155.7	16.7	-	14
0.40	99.24	1100	-	157.5	13.9	-	14
0.51 (L1)	98.2	900	C34	184	4.3	-	
0.51 (L1)	98.2	900	C34	181	6.6	-	
0.41 (L2)	98.6	900	C35	168	7.3	18.0	present work
0.41 (L2)	98.6	900	C35	152	7.7	17.3	
0.41 (L2)	98.6	1100	C27	149	7.2	20.2	
0.41 (L2)	98.6	1100	C27	148	8.7	23.6	

7. CONCLUSIONS

P/M products made from a wide range of prealloyed steel powders can yield hardness and tensile strength values equal to their wrought counterparts if the products are processed to attain densities in the vicinity of 98% of theoretical. This was accomplished in the present program by hot repressing preforms and by HERF processing. The impact strength and ductility of the materials produced, however, were inferior to those of wrought products. In the case of the hot repressing operation (limited deformation forging) two major factors were thought to contribute to low impact strength and low ductility: internal oxidation, during preform heating and transfer to the repressing dies, and lack of transverse metal flow during repressing, which would tend to further densify the material and help break up any continuous internal oxide films. With suitable attention to oxidation protection and steel composition, and if some transverse flow is permitted, there appears to be no insurmountable

barrier to routine attainment of properties closely approaching those of wrought materials in hot repressed P/M products. The present program was not intended to optimize procedures, processes, and materials, so that attainment of wrought properties was not generally expected.

The tensile properties of P/M products made from prealloyed steel powders by hot repressing or HERF processing are far superior to products made by cold pressing and sintering alone.

The HERF products tested exhibited unexpectedly low elongation and impact strength properties for material of such high density.

Individual prealloyed powders of essentially the same alloy composition were found to vary markedly from lot to lot, in ease of densification and resulting mechanical properties. The differences in mechanical properties tended to disappear when the various lots were processed to yield densities close to theoretical.

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APPENDIX

DATA COMPILATION

Mechanical and Physical Properties
of Powder Metallurgy Products Made
From Prealloyed, Heat Treatable Steel Powders

9. APPENDIX

FOREWARD TO DATA COMPILATION

The purpose of the data compilation presented here is to bring together the major part of the data currently available on heat-treatable steel P/M materials. Though data from heat-treated material have been emphasized in this compilation, some data are presented on unalloyed and nonheat-treated ferrous materials. Data considered to be proprietary by the concerns responsible for its generation and ultimate use are of course not included. Unfortunately, a large amount of the most advanced data extant fall in this category, and so are unavailable. It must be emphasized that the data presented here do not ordinarily represent the optimum properties obtainable from a given P/M material or part. Data have not been excluded because inferior properties were obtained. It is hoped, however, that sufficient information on the materials, processing, and testing accompanies the particular data summary to permit the reader to satisfactorily judge its value.

A number of extensive programs are currently underway, in the United States and abroad, which will yield procedures for economical attainment of near-optimum P/M properties. It appears that forging of P/M preforms will be the procedure used for obtaining the highest quality parts. Preform design, a subject beyond the scope of this data compilation, is one of the most critical items which must be resolved before optimum properties can be obtained in any given P/M part.

The diversity of the fabrication and testing methods employed by various investigators makes it impossible to treat the data concisely except as "data groups". The data of each individual investigating team are treated as an independent unit. The Table of Contents (following page) lists, in arbitrary order, the investigator(s) responsible for the data group and the steel compositions studied.

No claim is made for completeness of this data compilation. Some data have been omitted for imcompleteness or irrelevance, and some worthwhile data have been undoubtedly overlooked.

DATA COMPILATION

TABLE OF CONTENTS

Section

DATA COMPILATION

1. Data Group A

Reference: Summation of data presented in foregoing report.

Materials

Code	AISI Equivalent	Code	AISI Equivalent
A	4130	H	8620
B1	4130	I	4100 + 0.3C
B2	4130	J	4650
C	4130	K	4600 + 0.5C
D	4130	L1	4600 + 0.5C
E	4130	L2	4600 + 0.4C
F	4130	M	8600 + 0.5C
G	1040	N	9400 + 0.5C

The materials are described in detail in Figures 2 to 5, foregoing report.

Processing Notes

- All densities reported are bulk specimen densities, determined by measuring and weighing bars. These values are somewhat lower than the true specimen densities.
- All sintering was done is dissociated ammonia at either 1650°F or 2050°F, 1/2 hr.
- All austenitizing was done at 1575°F for 1/2 hr in endogas adjusted to the proper carbon potential.
- All austenitizing treatments ended with a water quench.
- All hot repressing operations (limited deformation forging) resulted in a lateral metal spread of $\leq$10%. In Task C, the die was preheated to 800°F.
- Hot repress preforms were not surface-protected in any way from oxidation during preheat (flowing argon) or transfer (in air) to the press.

Definition of Terms Used in Group A Data Compilation

P_1 = Die press, 50 ksi
P_2 = Die press, 80 ksi
P_3 = Die press, 100 ksi

I = Isostatic press, 50 ksi

H_1 = HERF, ∿200 ksi
H_2 = HERF, ∿300 ksi

S_1 = Sinter, 1650°F
S_2 = Sinter, 2050°F

T_1 = 1800°F
T_2 = 2000°F
T_3 = 2200°F

F_1 = Hot repress, 80 ksi
F_2 = Hot repress, 120 ksi
F_3 = Hot repress, 150 ksi
F_4 = Hot repress, 160 ksi

R = Cold repress, 80 ksi

Examples: $P_1S_2RS_2$ indicates an initial compaction at 50 ksi, followed by a 2050°F sinter, followed by a cold repress of 80 ksi and a 2050°F sinter

$P_3S_2F_4T_2$ indicates an initial compaction at 100 ksi, followed by a 2050°F sinter, followed by a hot repress operation: 160 ksi at 2000°F

H_1T_3 indicates a maximum pressure of about 200 ksi, with the powder at 2200°F

a = Compacts too fragile to handle

b = One or more samples broke during machining of tensile specimens, e.g., b(2) indicates two samples broke

c = Sample broke outside of reduced (gage) section during tensile test, e.g., within grips

GROUP A DATA

TYPE 4130

Nominal Composition: 0.3 C, 0.5 Mn, 1.0 Cr
Mesh: -100 0.2 Mo, 0.3 Si

Austenitized at 1575°F, Water Quench, Tempered at 900°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
P_1	B1	5.81						No machining attempted
P_1S_1	B1	5.83	B58					b(2)
P_1S_2	B1	5.97	B78		21.7 35.0	0.3 0.2		c
P_2	B1	6.27						No machining attempted
P_2S_1	B1	6.31	B76					b(2)
P_2S_2	B1 B2	6.43 6.60	B85	53.5	58.3	0.6	0.9	YS, UTS, TE arithmetic average of 11 spec.
P_3	B1 B2	6.48 6.78						No machining attempted
P_3S_1	B1	6.52	B67					b(2)
P_3S_2	B1	6.65	B91		61.0 57.3	0.5 0.4		
P_3S_2	B2	6.86	B85 B48	67.0 -	73.0 53.0	0.7 0.4	1.2 1.2	900°F temper 1100°F temper
$P_1S_1RS_2$	B1	6.60	B99		69.5 67.5	0.4 0.4		
$P_1S_2RS_2$	B1	6.55	B99		61.6 58.3	0.5 0.4		
$P_2S_1RS_2$	B1	6.85	B99	72.2	81.0 91.4	0.9 1.0		
$P_2S_2RS_2$	B1	6.66	B94		70.4	0.4		c(1)

GROUP A DATA

TYPE 4130

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
$P_3S_1RS_2$	B1	6.52	B94	87.4	89.9 94.6	0.6 0.6		
$P_3S_2RS_2$	B1	6.90	B98	79.4	89.9 82.5	0.7 0.4		
$P_1S_1F_3T_1$	B1	7.05	C20		13.8	0.1		c b(1)
$P_1S_1F_3T_3$	B1	7.18	C27	87.8	41.4 103	0.3 3.4		c
$P_1S_2F_3T_1$	B1	7.08	C23		70.8 52.8	0.5 0.2		
$P_1S_2F_3T_3$	B1	6.98	C27	114	126 67.6	2.5 0.3		
$P_2S_1F_3T_1$	B1	7.00	C25		47.0 47.5	0.2 0.2		
$P_2S_1F_3T_3$	B1	7.29	C32		126	0.4		b
$P_2S_2F_3T_1$	B1	7.11	C28		97.5 96.5	0.4 0.4		
$P_2S_2F_3T_3$	B1	7.08	B99		131 85.2	0.5 0.5		
$P_3S_1F_3T_1$	B1	7.16	C20		41.4 54.5	0.1 0.2		
$P_3S_1F_3T_3$	B1	7.21	C29	130	118 145	- 1.4		c
$P_3S_2F_3T_1$	B1	7.11	C27		94.5 93.0	0.4 0.2		
$P_3S_2F_3T_3$	B1	7.25	C31	145 118	152 121	1.8 1.1		"Best Process"
	B2	7.49					3.2	

GROUP A DATA

TYPE 4130

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
I	B1 B2	5.90 6.23						
IS_1	B1 B2	6.06 6.28	B75					b(2)
IS_2	B1	6.18	B81		49.0 51.1	0.5 0.5		
IF_3T_1	B1	7.51	C33		130	0.5		b(1)
IF_3T_3	B1	7.77	C37		140	0.8		b(1)
$IS_1F_3T_1$	B1	7.39	C32		97.5 74.5	0.5 0.3		
$IS_1F_3T_3$	B1	7.53	C39		159 147	0.5 0.5		"Best Process"
	B2	7.66					2.3	
$IS_2F_3T_1$	B1	7.40	C36	101	115 105	1.3 0.7		
$IS_2F_3T_3$	B1	7.44	C37	118 132	124 138	0.6 1.1		
H_1T_1	B1	7.70	C31		84.5 92.8	0.3 0.3		
H_2T_1	B1	7.74	C33	116	116 120	0.4 0.6		
H_1T_3	B1 B2	7.77 7.74	C24 C20	91.1	131 103	4.8		
H_2T_3	B1	7.72	C35	136	156 153	1.3 1.4		"Best Process"
	B2	7.73	C23		101	2.3	1.3	

GROUP A DATA

TYPE 4130

Process	Mat'l	Density gm/cm3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
P_3	I	7.03						Not machined
P_3S_2	I	7.03						Not machined
$P_3S_2F_3T_3$	I	7.50	C32	134 136	146 147	2.2 2.9	2.5	
I	I	6.60						Not machined
IS_1	I	6.62						Not machined
$IS_1F_3T_3$	I	7.79	C30		92.5 113	0.3 0.4	1.6	
H_2T_3	I	7.73	C30		77.0	0.2	1.0	Only one sample machined for test
H_2T_3	F	7.80	C32		77.0	0.2	1.6	Only one sample machined for test

GROUP A DATA

TYPE 4130

Note that tempering temperature is a variable. Task C Data.

Process	Mat'l	Density gm/cm^3	Temper, °F	Rockwell Hardness	YS ksi	UTS ksi	TE, percent	Charpy V-Notch Impact Energy, ft-lb
$P_3S_2F_1T_1$	B2	7.54	900	C20	102 104	114 114	4.8 3.8	1.8 (duplicate 1.9 tests)
$P_3S_2F_1T_1$	B2	7.54	1100	B95	90.5 90.5	100 98.4	5.0 5.0	2.2 2.4
$P_3S_2F_2T_1$	B2	7.59	900	C21	96.0 106	104 117	4.0 4.0	2.7 2.2
$P_3S_2F_2T_1$	B2	7.59	1100	B95	88.9 88.0	98.4 98.4	8.3 8.0	2.7 3.3
$P_3S_2F_3T_1$	B2	7.65	900	C23	99.2 100	113 114	5.1 4.4	3.3 2.9
$P_3S_2F_3T_1$	B2	7.65	1100	B98	92.0 89.6	102 99.2	8.8 7.5	2.3 4.3
$P_3S_2F_1T_2$	B2	7.61	900	C23	102 104	114 113	5.3 4.3	2.5 2.7
$P_3S_2F_1T_2$	B2	7.61	1100	B92	90.4 81.6	101 92.8	8.3 8.9	1.9 3.2
$P_3S_2F_2T_2$	B2	7.65	900	C20	96.0 84.0	107 95.0	4.7 4.0	3.2 2.5
$P_3S_2F_2T_2$	B2	7.65	1100	B95	81.6 90.4	90.4 100	8.3 7.3	4.3 4.6
$P_3S_2F_3T_2$	B2	7.64	900	C21	92.0 101	106 112	6.4 6.2	4.2 2.3
$P_3S_2F_3T_2$	B2	7.64	1100	B97	86.3 87.0	97.2 97.5	7.7 7.4	3.8 4.1
$P_3S_2F_1T_3$	B2	7.64	900	B98	95.0 84.0	108 88.0	3.8 4.4	3.3 2.9
$P_3S_2F_1T_3$	B2	7.64	1100	B94	80.9 82.4	91.2 92.4	7.4 10.4	4.8 4.5
$P_3S_2F_2T_3$	B2	7.67	900	C20	98.2 93.0	111 107	4.6 3.4	5.0 4.5
$P_3S_2F_2T_3$	B2	7.67	1100	C20	92.3 87.0	102 96.5	9.2 9.5	5.4 4.8
$P_3S_2F_3T_3$	B2	7.64	900	C22	88.9 85.0	99.0 101	6.9 4.1	4.5 4.5
$P_3S_2F_3T_3$	B2	7.64	1100	B95	89.0 105	89.0 105	6.5 7.7	5.5 4.9

GROUP A DATA

TYPE 1040

Nominal Composition: 0.4 C, 0.8 Mn
Mesh: -100

Austenitized at 1575 °F, Water Quench, Tempered at 900°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
P_2	G	6.69						Not machined
P_2S_2	G	6.72	B44	31.5 32.5	40.0 40.0	5.1 5.1	2.0	
P_3	G	6.90						Not machined
P_3S_2	G	6.94						Not machined
$P_3S_2F_3T_3$	G	7.67	B89	74.8 80.0	93.9 94.6	15.1 13.6	31.9	
I	G	6.60						Not machined
IS_1	G	6.62						Not machined
$IS_1F_3T_3$	G	7.79	B90	70.8 74.0	85.3 87.3	19.7 18.4	35.5	
H_2T_3	G	7.75	B86	73.5	87.5	19.0	38.7	Only one sample machined for test

GROUP A DATA

TYPE 4640

Nominal Composition: 0.4 C, 0.2 Mn, 0.5 Mo, 2.0 Ni, 0.03 Si
Mesh: -100

Austenitized at 1575 °F, Water Quench, Tempered at 900°F and 1100°F. Task C Data.

Process	Mat'l	Density, gm/cm^3	Temper, °F	Rockwell Hardness	YS ksi	UTS ksi	TE, percent	Charpy V-Notch Impact Energy, ft-lb
P_3	L2	7.20						
P_3S_2	L2	7.21	900	B95	119 122	129 131	2.4 1.4	1.9
P_3S_2	L2	7.21	1100	B92	111 110	112 119	0.7 2.9	2.3
$P_3S_2F_1T_1$	L2	7.64	900	C30	145 151	157 163	3.6 5.8	3.3 (duplicate 3.7 tests)
$P_3S_2F_1T_1$	L2	7.64	1100	C29	135 142	147 148	6.9 5.6	3.4 3.2
$P_3S_2F_2T_1$	L2	7.69	900	C31	157 159	170 171	4.1 5.6	5.9 5.3
$P_3S_2F_2T_1$	L2	7.69	1100	C29	146 157	157 145	9.2 9.7	6.4 6.9
$P_3S_2F_3T_1$	L2	7.76	900	C33	160 161	174 174	8.0 7.2	11.0 10.3
$P_3S_2F_3T_1$	L2	7.76	1100	C31	146 144	157 156	8.4 10.8	15.0 17.3
$P_3S_2F_1T_2$	L2	7.67	900	C31	153	171	5.5	3.5 4.5
$P_3S_2F_1T_2$	L2	7.67	1100	C27	140 140	152 153	8.5 10.0	5.8 5.0
$P_3S_2F_2T_2$	L2	7.72	900	C31	158 161	173 174	6.9 6.8	8.2 11.3
$P_3S_2F_2T_2$	L2	7.72	1100	C29	139 138	146 149	8.1 8.1	8.6 15.8
$P_3S_2F_3T_2$	L2	7.75	900	C32	150 152	162 163	7.6 7.1	15.0 12.7

GROUP A DATA

TYPE 4640. Note that the tempering temperature is a variable. Task C Data.

Process	Mat'l	Density gm/cm^3	Temper, °F	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch Impact Energy, ft-lb
$P_3S_2F_3T_2$	L2	7.75	1100	C29	142 138	148 148	9.5 8.7	20.0 (duplicate 21.0 tests)
$P_3S_2F_1T_3$	L2	7.70	900	C30	150 147	161 157	4.3 5.9	8.3 5.2
$P_3S_2F_1T_3$	L2	7.70	1100	C27	132 138	143 147	10.1 8.6	15.6 6.0
$P_3S_2F_2T_3$	L2	7.73	900	C29	157 161	163 165	5.9 5.2	10.3 10.5
$P_3S_2F_2T_3$	L2	7.73	1100	C29	139	148	8.6	20.3 17.2
$P_3S_2F_3T_3$	L2	7.75	900	C35	159 163	168 152	7.3 7.7	18.0 17.3
$P_3S_2F_3T_3$	L2	7.75	1100	C27	142 138	149 148	7.2 8.7	20.2 23.6

GROUP A DATA

TYPE 4650

Nominal Composition: 0.5 C, 0.2 - 0.5 Mn, 0.2 - 0.5 Mo, 2.0 Ni, 0.02 - 0.5 Si
Mesh: -100

Austenitized at 1575°F, Water Quench, Tempered at 900°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch, ft-lb	Remarks
	J	5.83						
P_1	K	6.10						No machining attempted
	L1	6.46						
	J	5.78	B80					b (2)
P_1S_1	K	6.03	B56					b (2)
	L1	6.45	B43	† †	36.5 33.8	0.2 0.4		
	J	5.95	B78					b (2)
P_1S_2	K	6.17	B81	†	32.0	0.3		b (1)
	L1	6.43	B89	† 72.3	75.8 77.5	0.2 0.6		
	J	6.18						
P_2	K	6.58						No machining attempted
	L1	6.69						

*Yield strength data unobtainable, due to extensometer problems.
†Yield strength data not obtainable due to characteristics of material.

GROUP A DATA

TYPE 4650

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch ft-lb	Remarks
	J	6.13	B85					b (2)
P_2S_1	K	6.48	B62	†	8.0	0.2		b (1) c
	L1	6.91	B54	82.0 77.0	97.0 83.0	1.0 1.5		
	J	6.31	B91	† †	39.0 41.0	0.5 0.3	0.9	
P_2S_2	K	6.65	B93	† †	68.5 69.7	0.5 0.4	1.0	
	L1	6.93	B98	† 113	107 116	0.4 1.0	1.4	
	J	6.33						
P_3	K	6.79						No machining attempted
	L1	7.11						
	J	6.38	B88					b (2)
P_3S_1	K	6.69	B79	†	15.8	0.2		b (1) c
	L1	7.08	B58	33.0 31.5	36.0 35.0	1.4 1.0		
	J	6.59	B92	† †	55.3 59.0	0.3 0.4	3.2	
P_3S_2	K	6.85	B94	† †	63.8 69.0	0.3 0.3		
	L1	7.15	C21	122 125	132 137	1.2 1.2		
	J	6.40	B86	† *	66.3 60.0	0.5 0.7		
$P_1S_1RS_2$	K	6.82	B91	† *	76.1 76.0	0.3 0.4		
	L1	7.05	B99	112 116	124 127	1.2 1.4		

*Yield strength data unobtainable, due to extensometer problems.
†Yield strength data not obtained because of material characteristics.

GROUP A DATA

TYPE 4650

Process	Mat'l	Density gm/cm³	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch, ft-lb	Remarks
	J	6.31	B87	† *	52.0 50.0	0.4 0.5		
$P_1S_2RS_2$	K	6.44	B86	† *	58.5 62.0	0.3 0.3		
	L1	6.56	B83	† 82.5	88.0 87.8	0.2 0.6		
	J	6.52	B90	† 8	64.7 57.8	0.4 0.3		
$P_2S_1RS_2$	K	6.96	C24	*	87.0	0.4		b (1)
	L1	7.33	C24	135 137	145 150	2.2 1.7		
	J	6.52	B92	* †	65.0 64.0	0.5 0.4		
$P_2S_2RS_2$	K	6.82	B97	* †	78.0 91.9	0.5 0.4		
	L1	7.00	C20	108 110	128 120	0.7 1.3		
	J	6.68	B96	† *	65.7 67.5	0.3 1.0		
$P_3S_1RS_2$	K	7.08	C26	† *	41.6 101	1.0 0.5		
	L1	7.38	C28	138 143	152 157	2.0 2.3		
	J	6.70	B96	† *	72.0 66.3	0.4 0.7		
$P_3S_2RS_2$	K	6.98	C23	* †	90.0 105	0.6 1.0		
	L1	7.19	C21	127 126	138 133	1.5 1.8		
	J	7.59	C43	† *	89.0 96.0	0.3 0.9		
$P_1S_1F_3T_1$	K	7.60	C39					b (2)
	L1	7.70	C30	152 135	159 143	2.8 3.1		

*Yield strength data unobtainable, due to extensometer problems.
†Yield strength data not obtained because of material characteristics.

GROUP A DATA

TYPE 4650

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch, ft-lb	Remarks
	J	7.67	C39	† *	176 157	0.6 1.0		
$P_1S_1F_3T_3$	K	7.70	C39	180 *	183 152	2.1 0.6		c
	L1	7.65	C36	168 169	177 177	4.8 4.9		
	J	7.69	C41	† *	145 193	0.5 2.0		
$P_1S_2F_3T_1$	K	7.64	C39	185 *	189 188	2.6 1.9		
	L1	7.84	C37	168 171	180 182	6.5 5.2		
	J	7.72	C39	175 *	184 137	2.4 2.2		
$P_1S_2F_3T_3$	K	7.67	C38	172 *	178 160	2.3 1.1		
	L1	7.72	C36	163 167	174 178	6.0 5.8		
	J	7.53	C42	† *	89.0 94.0	0.3 0.4		
$P_2S_1F_3T_1$	K	7.61	C39	† *	163 155	2.3 0.6		
	L1	7.77	C26	148 113	151 125	3.2 3.2		
	J	7.61	C43					b (2)
$P_2S_1F_3T_3$	K	7.64	C40	*	150	0.8		b (1)
	L1	7.60	C36	174 151	184 152	5.1 0.7		
	J	7.63	C39	† *	168 162	0.5 1.3		
$P_2S_2F_3T_1$	K	7.67	C38	† *	87 180	0.4 1.3		
	L1	7.80	C38	174 178	184 188	6.2 5.9		

*Yield strength data unobtainable, due to extensometer problems.
†Yield strength data not obtained because of material characteristics.

GROUP A DATA

TYPE 4650

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch ft-lb	Remarks
	J	7.66	C38	† *	177 146	1.0 1.2		
$P_2S_2F_3T_3$	K	7.68	C38	† *	172 178	0.9 2.1		
	L1	7.77	C35	167 *	180 185	5.9 6.2		
	J	7.60	C43	*	87.8	0.7		b (1)
$P_3S_1F_3T_1$	K	7.64	C35	*	128	0.6		b (1)
	L1	7.76	C32	153 156	158 160	3.6 2.6		
	J	7.59	C39					b (2)
$P_3S_1F_3T_3$	K	7.62	C41	† *	153 142	1.6 1.2		
	L1	7.67	C37	173 175	180 185	3.4 4.0		
	J	7.65	C38	† *	177 158	1.1 1.7		
$P_3S_2F_3T_1$	K	7.66	C40	† *	177 171	2.0 0.7		
	L1	7.81	C38	173 178	185 189	6.2 3.6		
	J	7.73	C41	† *	197 150	0.5 1.2		
$P_3S_2F_3T_3$	K	7.67	C39	172 *	175 175	2.0 1.1		
	L1	7.72	C34	168 171	181 184	6.6 4.3		

* Yield strength data unobtainable, due to extensometer problems.

† Yield strength data not obtained because of material characteristics.

GROUP A DATA

TYPE 4650. Note that the tempering temperature is a variable. Task C Data.

Process	Mat'l	Density gm/cm^3	Temper °F	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch Impact Energy, ft-lb
$P_3S_2F_1T_1$	J	7.42	900	C34	- -	148 144	0.6 0.5	1.8 (duplicate 1.5 tests)
$P_3S_2F_1T_1$	J	7.42	1100	C29	- 146	149 148	0.5 1.2	1.5 1.7
$P_3S_2F_2T_1$	J	7.55	900	C35	- -	159 165	0.4 0.5	2.1 2.3
$P_3S_2F_2T_1$	J	7.55	1100	C32	152 153	156 158	1.3 1.2	2.8 2.8
$P_3S_2F_3T_1$	J	7.64	900	C39	180 177	187 163	1.4 1.1	2.1 2.8
$P_3S_2F_3T_1$	J	7.64	1100	C32	148 152	149 157	0.9 1.1	1.8 2.4
$P_3S_2F_1T_2$	J	7.52	900	C34	163 164	163 166	0.6 0.7	2.5 2.2
$P_3S_2F_1T_2$	J	7.52	1100	C31	146 142	149 143	1.4 0.7	2.3 3.2
$P_3S_2F_2T_2$	J	7.63	900	C36	170 170	174 175	1.0 1.1	2.8 2.4
$P_3S_2F_2T_2$	J	7.63	1100	C32	148 147	150 152	0.8 1.1	2.9 3.5
$P_3S_2F_3T_2$	J	7.67	900	C36	172 173	173 181	0.9 1.3	2.2 2.5
$P_3S_2F_3T_2$	J	7.67	1100	C33	152 151	158 158	1.1 2.2	2.7 3.5
$P_3S_2F_1T_3$	J	7.53	900	C34	174 166	178 170	1.0 0.9	1.7 2.3
$P_3S_2F_1T_3$	J	7.53	1100	C32	151 151	154 159	0.9 1.7	3.0 -
$P_3S_2F_2T_3$	J	7.65	900	C36	- 172	181 182	- 1.2	3.0 2.0
$P_3S_2F_2T_3$	J	7.65	1100	C31	147 147	151 161	1.0 5.7	3.5 4.4
$P_3S_2F_3T_3$	J	7.69	900	C36	170 170	170 174	0.8 1.0	3.2 3.1
$P_3S_2F_3T_3$	J	7.69	1100	C34	149	158	3.4	6.0 3.7

GROUP A DATA

TYPE 8620

Nominal Composition: 0.2 C, 0.8 Mn, 0.2 Mo,
Mesh: -100 0.7 Ni, 0.4 Cr, 0.3 Si

Mechanical Properties Determined on Samples
with 15-mil Carburized Case.
Austenitized at 1575°F, Water Quench, Tempered at 450°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch, ft-lb	Remarks
P_2	H	6.59						Not machined
P_2S_2	H	6.67	B74		57.5 55.6	0.3 0.3		
P_3	H	6.86						Not machined
P_3S_2	H	6.92	C39 C29	- -	145 111	0.7 0.5	1.3 1.2	Tempered 450°F Tempered 900°F
$P_3S_2F_3T_3$	H	7.65	C53	188 188	214 201	1.1 2.2	1.8	
I	H	6.25						Not machined
IS_1	H	6.35						Not machined
$IS_1F_3T_3$	H	7.73	C54	191 160	196 173	1.1 1.6	2.0	
H_2T_3	H	7.75	C53	183 170	194 183	0.8 1.8	1.7	

GROUP A DATA

TYPE 8620. Note that tempering temperature is a variable. Task C Data

Process	Mat'l	Density gm/cm^3	Temper, °F	Rockwell Hardness	YS ksi	UTS ksi	TE Percent	Charpy V-Notch Impact Energy, ft-lb
$P_3S_2F_1T_1$	H	7.55	900	C39	164 163	165 165	0.7 0.9	1.5 (duplicate - tests)
$P_3S_2F_1T_1$	H	7.55	450	C52	- 193	202 201	- 0.9	1.7 1.9
$P_3S_2F_2T_1$	H	7.60	900	C40	167 160	170 165	0.9 1.1	1.6 1.6
$P_3S_2F_2T_1$	H	7.60	450	C53	201 196	208 211	0.9 1.0	1.8 1.8
$P_3S_2F_3T_1$	H	7.67	900	C40	- 164	173 167	- 0.9	1.7 1.6
$P_3S_2F_3T_1$	H	7.67	450	C54	208 198	216 198	1.1 0.9	1.9 1.7
$P_3S_2F_1T_2$	H	7.58	900	C40	- 164	165 170	0.6 0.9	1.7 1.6
$P_3S_2F_1T_2$	H	7.58	450	C53	196 192	201 207	0.8 1.0	1.8 1.9
$P_3S_2F_2T_2$	H	7.66	900	C41	166 169	171 175	0.9 1.0	1.7 1.6
$P_3S_2F_2T_2$	H	7.66	450	C53	207 192	209 206	0.9 1.1	1.8 1.8
$P_3S_2F_3T_2$	H	7.66	900	C43	169 169	177 174	1.0 0.9	1.7 1.7
$P_3S_2F_3T_2$	H	7.66	450	C55	193 196	214 219	1.0 1.3	1.8 1.8
$P_3S_2F_1T_3$	H	7.63	900	C41	- 166	168 172	- 0.9	1.5 1.6
$P_3S_2F_1T_3$	H	7.63	450	C56	201 204	206 216	1.0 1.0	2.0 2.1
$P_3S_2F_2T_3$	H	7.66	900	C42	166 163	171 169	1.1 1.0	1.7 1.7
$P_3S_2F_2T_3$	H	7.66	450	C53	187 193	212 208	1.2 1.1	1.9 2.3
$P_3S_2F_3T_3$	H	7.65	900	C40	164 163	171 169	1.1 1.1	1.7 1.9
$P_3S_2F_3T_3$	H	7.65	450	C54	184	212	1.2	2.0 2.0

GROUP A DATA

TYPE 8650

Nominal Composition: 0.5 C, 0.6 Ni, 0.1 Mn, 0.5 Mo, 0.6 Cr
Mesh: -100

Austenitized at 1575°F, Water Quench, Tempered at 900°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch ft-lb	Remarks
P_1	M	6.31						No machining attempted
P_1S_1	M	6.30	B13		23.9	0.2		b (1)
P_1S_2	M	6.32	B72	45.0	46.0 40.2	0.6 0.3		
P_2	M	6.81						No machining attempted
P_2S_1	M	6.77	B31		13.5 19.7	0.2 0.3		
P_2S_2	M	6.81	B88	80.5 71.0	81.0 75.8	0.4 1.4	1.2	
P_3	M	7.01						No machining attempted
P_3S_1	M	6.97	B95	80.5	88.5	0.7		b (1)
P_3S_2	M	7.00	B89	81.3	86.0	0.5		b (1)
$P_1S_1RS_2$	M	6.93	B91	80.5	89.9 89.3	1.1 1.2		
$P_1S_2RS_2$	M	6.88	B92	85.0 77.7	91.6 89.5	1.4 0.8		
$P_2S_1RS_2$	M	7.09	B96	100 98	106 108	0.5 2.6		
$P_2S_2RS_2$	M	7.06	B91	90.0 96.0	96.0 103	0.5 1.6		

GROUP A DATA

TYPE 8650

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch ft-lb	Remarks
$P_3S_1RS_2$	M	7.20	B96	95.3 92.0	104 111	0.7 1.6		
$P_3S_2RS_2$	M	7.16	B98	93.3 94.0	107 103	0.9 1.0		
$P_1S_1F_3T_1$	M	7.64	B86	55.8 64.5	62.3 62.0	1.8 1.4		
$P_1S_1F_3T_3$	M	7.82	C37	155 163	157 170	0.8 4.2		
$P_1S_2F_3T_1$	M	7.68	C34	157 160	166 168	3.4 2.5		
$P_1S_2F_3T_3$	M	7.83	C32	154 153	163 167	4.8 5.0		
$P_2S_1F_3T_1$	M	7.74	B89	61.3 58.0	64.0 59.6	2.2 0.9		
$P_2S_1F_3T_3$	M	7.70	C36	168 113	173 124	1.1 1.1		
$P_2S_2F_3T_1$	M	7.83	C34	167 160	173 171	2.4 3.8		
$P_2S_2F_3T_3$	M	7.83	C35	157 158	166 165	4.2 5.0		
$P_3S_1F_3T_1$	M	7.68	B89	64.7 65.1	68.5 68.6	2.1 1.4		
$P_3S_1F_3T_3$	M	7.90	C35	151 150	160 161	3.8 2.6		
$P_3S_2F_3T_1$	M	7.80	C32	149 147	158 159	2.8 3.9		
$P_3S_2F_3T_3$	M	7.81	C33	145 123	155 156	3.7 5.0		

GROUP A DATA

TYPE 9450

Nominal Composition: 0.5 C, 0.3 Ni, 0.2 Mn, 0.3 Mo, 0.3 Cr
Mesh: -100

Austenitized at 1575°F, Water Quench, Tempered at 900°F

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch ft-lb	Remarks
P_1	N	6.33						No machining attempted
P_1S_1	N	6.35	B5	17.8 17.6	22.4 20.2	1.5 1.1		
P_1S_2	N	6.30	B70	43.7 44.5	46.8 47.0	0.6 1.0		
P_2	N	6.86						No machining attempted
P_2S_1	N	6.86	B26	54.5 23.1	75.8 29.4	3.8 2.6		
P_2S_2	N	6.85	B80	61.1 59.0	66.0 65.4	0.6 1.0	1.5	
P_3	N	7.05						No machining attempted
P_3S_1	N	7.03	B40	24.5 25.9	32.5 33.3	2.2 2.4		
P_3S_2	N	7.01	B83	71.5 73.0	78.0 78.1	0.8 0.8		
$P_1S_1RS_2$	N	7.01	B93	83.0 75.0	93.5 93.0	0.8 2.0		
$P_1S_2RS_2$	N	6.87	B78	67.3 66.0	77.0 74.4	0.9 1.6		
$P_2S_1RS_2$	N	7.18	B96	88.5 83.5	103 93.3	1.4 1.6		
$P_2S_2RS_2$	N	7.05	B91	74.5	86.0 87.2	0.2 1.6		

GROUP A DATA

TYPE 9450

Process	Mat'l	Density gm/cm^3	Rockwell Hardness	YS ksi	UTS ksi	TE percent	Charpy V-Notch ft-lb	Remarks
$P_3S_1RS_2$	N	7.23	B91	84.0 88.8	109 102	1.7 1.3		
$P_3S_2RS_2$	N	7.17	B96	75.0 84.5	94.9 95.5	2.2 0.9		
$P_1S_1F_3T_1$	N	7.64	B88	65.6 67.9	80.6 82.0	7.4 7.5		
$P_1S_1F_3T_3$	N	7.72	C30	122 113	145 133	6.5 7.6		
$P_1S_2F_3T_1$	N	7.63	C31	159 140	172 158	4.2 5.0		
$P_1S_2F_3T_3$	N	7.72	C32	153 138	166 153	5.7 6.2		
$P_2S_1F_3T_1$	N	7.70	B85	65.8 70.5	76.5 84.8	7.0 7.8		
$P_2S_1F_3T_3$	N	7.71	C30	109 109	130 127	7.3 7.5		
$P_2S_2F_3T_1$	N	7.77	C30	112 112	128 133	3.5 7.6		
$P_2S_2F_3T_3$	N	7.83	C30	131 130	145 146	6.1 6.4		
$P_3S_1F_3T_1$	N	7.70	B87	68.0 74.0	80.3 87.3	7.4 8.0		
$P_3S_1F_3T_3$	N	7.75	C30	113 112	134 132	6.3 7.0		
$P_3S_2F_3T_1$	N	7.80	C30	124 105	142 137	5.5 4.3		
$P_3S_2F_3T_3$	N	7.86	C30	120 122	135 138	7.9 7.8		

2. <u>Data Group B</u>

Reference: 10

<u>Materials</u>

Steel: Type 4600, A. O. Smith-Inland EMP
See Table 1-A for powder composition and characteristics.
Carbon: Graphite, Southwestern No. 1651.

<u>Processing Summary</u>

<u>Preform Preparation</u>: Preforms were made from steel admixed with 0.45 C plus 0.75% zinc stearate.

Three powder sizes were used: as-received (-28 +200) and fine (-200).

Preform sintering was done at 2100°F for 40 min in endogas at 40°F dewpoint.

<u>Forging</u>: Forging was limited-deformation type, with approximately 30% lateral flow (0.320 in. to 0.418 in.).

Preheat: Approximately five minutes in dissociated ammonia.
Ram speed: 2.6 ips.

No atmospheric protection was provided during transfer, forging, or cooling.

Heat treatment: Austenitizing was done at 1525°F for 45 min, followed by oil quenching. To complete the martensite transformation, forgings were held at -120°F for 12 hr. They were then stress relieved at 300°F for 30 min, and tempered at 1100°F.

<u>Group B Data</u>

The tensile properties of the P/M steel forgings are presented in Table 2-A.

TABLE 1-A

Properties of As-Received EMP 4600 Steel Powder[a]

Chemical Analysis, w/o		
Nickel		2.03
Molybdenum		0.55
Carbon		0.01
Manganese		0.04
Phosphorus		0.005
Sulfur		0.009
Silicon		0.010
Oxygen		0.12
Hydrogen Loss		0.15
Physical Properties		
Apparent Density,	g/cc	2.92
Flow,	sec/50 g	25.4
Green Density[b]	g/cc	6.50
Green Strength[b]	psi	1370
Tyler Sieve Analysis, w/o		
- 28 + 35 mesh		trace
- 35 + 48		1.5
- 48 + 60		6.2
- 80 + 100		6.5
-100 + 150		14.5
-150 + 200		21.5
-200 + 250		5.0
-250 + 325		19.5
-325		23.0

a - Lot No. 124. Values furnished by supplier.

b - At 30 tsi with 0.75% zinc stearate.

NOTE: Supplied at -28 mesh by request. This type is normally supplied at -80 mesh.

TABLE 2-A

Tensile Properties of P/M Steel Forgings

Experimental Variables				Properties of Forging						
Powder Size	Preform		Preheat, F	Density,[a] %	Carbon, %	Hard., R_c	Tensile[b]			
	Den., %	Cond.					T.S., ksi	Y.S., ksi	Elong., %	R.A., %
As-Rec'd	75	Sint.	1750	98.5	0.48	34-33	156.5	145.3	14	43
Coarse	81			98.9	0.46	34-33	152.2	140.0	13	42
Fine	81			98.6	0.51	35-35	153.4	142.0	14	43

a - Portion tested was probably >99%.

b - Round specimen with 0.18 in. gage diameter; elongation in 0.9 in; 0.1 in./min crosshead speed; 0.2%-offset Y.S.

3. Data Group C

Reference: 17

Materials

Steel - 4600, prealloyed, A. O. Smith-Inland

Iron - EMP 300, A. O. Smith-Inland

Molybdenum - Fansteel P/M, 200 mesh

Nickel - International Nickel, Type 123

Carbon - Southwestern Graphite, No. 1651

Compositions of the steels investigated are given in Table 3-A.

TABLE 3-A
Composition of Steels Used in Study

Steel Type		Alloy Element, wt% C	Mn	Si	Ni	Mo
Wrought Control Materials	4620 4640					
Prealloy	4600 + 0.2C 4600 + 0.3C 4600 + 0.4C	Added	0.20	--	2.00	0.50
Elemental	4640	Added	--	--	1.85	0.50

Processing Summary

Preform Preparation: The preform compacts made from the various blends had green densities in the range 6.5 to 6.7 gm/cm^3. Each preform was simultaneously sintered and preheated for forging in one of two ways, viz., by furnace heating in hydrogen for 15 min at 2000°F, or by induction heating, in air, to 2000°F. The hot samples were then immediately forged.

Forging Procedure: Not described in detail. Forgings had density of >98% of theoretical.

Heat Treatment: All material, wrought and otherwise, was normalized at 1650°F prior to further heat treatment. Material tested in both normalized condition, as well as austenitized, quenched, and tempered. Heat treatment was done by a commercial heat-treating concern.

Group C Data

Mechanical properties resulting from furnace heating and induction heating of 4620 and 4630 preforms are given in Table 4-A. The comparison between furnace heating and induction heating of elemental and prealloyed 4640 is presented in Tables 5-A and 6-A, respectively.

TABLE 4-A

Furnace Heating versus Induction Heating of Prealloyed 4620 and 4630

		4620	4630
Hardness (Rockwell)	Wrought	B-91	-
	Furnace	B-90	B-92
	Induction	B-89	B-92
Ultimate Tensile psi	Wrought	92,500	-
	Furnace	89,300	95,300
	Induction	88,400	96,300
Yield Strength psi, 0.2% Offset	Wrought	72,100	-
	Furnace	68,600	72,300
	Induction	70,500	80,100
Elongation % in 1 in.	Wrought	21.4	-
	Furnace	19.3	18.1
	Induction	15.6	14.5
Charpy Impac. ft-lb	Wrought	122.0	-
	Furnace	65.0	42.0
	Induction	32.0	28.0

TABLE 5-A

Furnace Heating versus Induction Heating of Elemental 4640

		Normalized	Tempers 400°F	Tempers 800°F
Hardness (Rockwell)	Wrought	B-86	C-45	C-36
	Furnace	B-69	C-43	C-27
	Induction	B-54	C-25	B-88
Ultimate Strength psi	Wrought	115,400	274,000	182,200
	Furnace	82,800	257,000	143,800
	Induction	75,500	180,300	113,400
Yield Strength psi, 0.2% Offset	Wrought	73,500	206,600	173,200
	Furnace	37,400	185,600	120,700
	Induction	36,400	115,900	80,200
Elongation % in 1 in.	Wrought	17.1	11.0	12.0
	Furnace	20.0	4.6	8.1
	Induction	24.0	3.5	9.2
Charpy Impact ft-lb	Wrought	39.0	25.0	39.0
	Furnace	11.0	9.0	7.0
	Induction	10.0	9.0	9.0

TABLE 6-A

Furnace Heating versus Induction Heating of Prealloyed 4640

		Normalized	Tempers 400°F	Tempers 800°F
Hardness (Rockwell)	Wrought	B-86	C-45	C-36
	Furnace	B-86	C-43	C-35
	Induction	B-86	C-47	C-35
Ultimate Tensile psi	Wrought	115,400	274,000	182,200
	Furnace	100,300	276,100	185,400
	Induction	110,200	295,300	198,500
Yield Strength psi, 0.2% Offset	Wrought	73,500	206,600	173,200
	Furnace	68,000	203,500	167,700
	Induction	82,400	210,000	185,000
Elongation % in 1 in.	Wrought	17.1	11.0	12.0
	Furnace	14.3	6.1	6.8
	Induction	12.4	3.2	4.2
Charpy Impact ft-lb	Wrought	39.0	25.0	39.0
	Furnace	19.0	9.0	9.5
	Induction	8.0	8.5	5.0

4. Data Group D

Reference: 14

Materials

A. O. Smith Inland materials:
1040 carbon steel, resulfurized;
8600, 9400, and 4600 with graphite additions.

Processing Summary

Two processes were employed to yield mechanical property data: high-energy-rate-forming (Dynapak) and forging.

High-Energy-Rate-Forming

Blanks 1 1/2 in. thick were forged at 1700°F in one blow to 1 in. thick sections by Dynapak. The resulting densities were 98 - 99%. The samples were oil quenched from 1650°F and tempered. The preform density was 6.7 gm/cm^3.

Forging

In order to determine the optimum properties of alloyed steel powder, slugs of -80 mesh alloy powder mixed with 0.5 wt % graphite were prepared without admixed lubricant.

The slugs were pressed to a density of 7.05 - 7.40 gm/cm^3, double sintered in cracked ammonia at 2050°F, and encapsulated in 2 in. diameter steel tubing. The resulting encapsulated preforms were then either hot forged into 1 in. × 10 in. bars, with an approximate hot reduction of 5:1, or upset forged into 5/8 in. thick discs with an approximate hot reduction of 3.2:1. The final composition of the forgings is given in Table 7-A.

TABLE 7-A

Compositions of Final Forgings

	C	Mn	Si	Cr	Ni	Mo	O_2	N_2	H_2
Blend A	0.37	0.17	0.020	0.080	1.73	0.44	0.030	0.003	0.0001
Blend B	0.41	0.29	0.13	0.58	0.63	0.40	0.185	0.001	0.0007

The mechanical properties of samples cut from P/M crankshaft forgings are also presented.

Group D Data

The mechanical properties of the P/M products resulting from the study are presented in Tables 8-A through 11-A.

TABLE 8-A

Tensile Properties of High-Energy-Rate-Formed Material

Type	Tempering Temp. °F	Yield Strength psi	Ultimate Strength psi	Elongation %	Reduction of Area %
1040	400	68,000	90,000	27.5	18.3
4640	700	185,000	203,000	7.0	7.7
4640	1000	155,000	167,000	9.0	18.1
8650	700	96,000	122,000	5.0	3.9
9440	700	79,000	108,000	14.0	25.8

TABLE 9-A

Tensile Properties
of "Optimized Properties" Forgings

Type	Forged Density %	Forging Temp. °F	Forging Ratio	Yield Strength 0.2% Offset ksi	Ultimate Yield Strength ksi	Elongation %	Reduction of Area %
Blend A	99.63	1700	5:1	138.9	148.8	16.4	46.5
4640	99.63	1950	5:1	145.3	157.2	16.5	45.9
	*99.76	1950	5:1	151.5	163.9	12.0	33.0
	99.89	2100	5:1	144.7	155.7	16.7	48.8
	99.11	1700	3.2:1	143.8	157.0	13.6	46.0
	99.24	2100	3.2:1	142.4	157.5	13.9	46.0
Blend B	98.60	1700	5:1	144.8	151.0	7.0	11.8
8640	98.73	1950	5:1	155.4	164.1	9.0	22.6
	*98.73	1950	5:1	146.6	155.0	5.6	7.4
	98.98	2100	5:1	152.0	155.5	11.3	26.5
	98.22	1700	3.2:1	153.7	161.2	10.3	28.0
	98.60	2100	3.2:1	144.0	160.6	9.7	20.5

* Homogenized, 2300°F - 3 hr prior to heat treatment.

Test specimens cut from encapsulated hammer forged bars. 5:1 ratio are 0.505 in. diameter tensile bars, 1650°F water quenched + 1050°F. 3.2:1 ratio are 0.180 in. diameter Hounsfield bars, 1650°F oil quenched + 1000°F.

TABLE 10-A

Impact Data from 4640 Forging Hot Reduced 3.2:1 at 1950°F

Density 7.84 g/cc (99.76%)

Heat Treated 1650°F water quench
1100°F temper
30 Rockwell C

Cnemical Analysis: Percent by weight

C	Mn	Si	Ni	Mo	Cr	O_2
0.36	0.17	0.02	1.82	0.47	0.08	0.030

Half-standard Charpy notched bars tested at room temperature.

	U Notch	Vee Notch
Energy ft-lb	20.8	11.4
Contraction Under Notch	11.2%	7.6%
Fracture Appearance	100% Shear	100% Shear

TABLE 11-A

Longitudinal Tensile Properties of Crankshaft Core

Type	Forged Density g/cc	Tempering Temp. °F	Tempered Hardness R - C	Yield Strength ksi	Tensile Strength ksi	Elongation % in 1 in.	Reduction of Area %
4645	7.86	700	44/46	187.4	204.9	9	42.5
8650	7.81	700	45/47	203.6	231.4	5	5.0
*1150	7.83	400	20/24	72.3	100.1	16	47.0

* 0.2% Sulfur

Test specimens cut from forged crankshaft. Forged in conventional closed die from 1 7/8 in. diameter preforms. Forging temperature 1600°F. Oil quenched from 1650°F and tempered.

5. Data Group E

References: 1 and 8

Materials

Steels: "Commercially available" types 1050, 4630, modified 4630 (low nickel), and 8630 steel powders.

Processing Summary

The powder was admixed with the appropriate amount of graphite, a lubricant added, and briquettes pressed to 80% of theoretical density. The briquettes were then sintered at 2050°F for 20 minutes. After sintering, the bars were heated to 1800°F under a controlled atmosphere. The bars were then transferred in air into a rectangular die cavity where they were hot densified (hot repressed) to 98% of theoretical density. The samples were then annealed, machined, heat treated, and tested.

Group E Data

The tensile and impact properties of the four P/M steel products studied are presented in Tables 12-A and 13-A, respectively.

Additional Comments

Standard R. R. Moore fatigue tests showed the modified 4630 alloy to have the highest endurance limit of the four steels chosen for study, viz., 60,000 psi.

TABLE 12-A

Tensile Properties of Hot Densified Powder Metal Alloys

Material	Yield Stress 0.2% Offset psi	Ultimate Strength psi	Elongation % in 1 in. gage length	Reduction of Area %	Modulus of Elasticity $\times 10^6$	Hardness R_C
			400°F Draw			
1050	83,000	100,000	11.3	17.8	32.0	28
Mod 4630	193,000	215,000	6.5	10.5	28.0	42
4630	178,000	214,000	6.5	22.0	25.5	42
8630	174,000	233,000	7.0	18.0	26.0	42
			800°F Draw			
Mod 4630	163,000	173,000	9.0	22.0	29.5	34
4630	146,000	171,000	10.5	22.0	25.5	35
8630	151,000	174,000	11.0	24.0	26.5	35
			1000°F Draw			
Mod 4630	157,000	167,000	11.0	23.0	27.7	30
4630	148,000	167,000	14.0	22.5	28.0	32
8630	143,000	166,000	12.5	30.0	27.5	34

TABLE 13-A

Room Temperature Impact Strength

Alloy	V-Notched Charpy ft-lb	Unnotched Charpy ft-lb	Hardness R_C
1050	6.5	-	28
Mod 4630	6.0	-	42
4630	6.5	80.0	42
	9.0	-	39
	11.0	-	32
8630	8.5	68.0	42
	10.5	-	37
	17.5	-	30
8615	70.0	-	18

6. <u>Data Group F</u>

Reference: 11

Materials

Steel of a nominal 4640 composition was studied.
Description of the prealloyed 4600 and elemental powders is given in Table 14-A.

Processing Summary

Atomized and mixed elemental powders, prepared to a nominal 4640 steel composition (2.0 Ni, 0.25 Mo - 0.40 C - balance iron) were pressed and sintered to comparable density levels in the range 6.45 to 7.25 gm/cm^3. Sintering was carried out at either 2050°F for 30 minutes or 2400°F for 60 min,in dissociated ammonia. The specimens were subsequently heat treated and tested.

Group F Data

The mechanical properties of sintered atomized and sintered elemental 4640 powder compacts is given in Table 15-A. The heat-treated properties of the atomized and mixed elemental 4640 powders sintered at 2050°F and 2400°F are given in Tables 16-A and 17-A, respectively.

TABLE 14-A

Raw Powders Used

Alloy or Element	4600	Iron	Nickel	Molybdenum	Graphite
Type	Atomized	Atomized	Carbonyl	Electrolytic	Natural
Apparent Density, g/cc	3.28	2.95	2.17	1.50	-
Flow, sec.	22.2	25.0	No Flow	No Flow	No Flow
Avg. Particle Size, Microns	-	-	5.1	3.90	0.7
Screen Analysis, %					
- 80 + 100	0.1	3.0	-	-	-
-100 + 150	15.6	14.0	0.1	-	-
-150 + 200	25.5	22.0	2.3	-	-
-200 + 250	9.4	10.0	1.5	-	-
-250 + 325	14.9	21.0	5.0	-	-
-325	34.5	30.0	91.1	100.0	100.0
Chemical Analysis, %					
Fe	Bal	99.5	0.003	0.01	-
Ni	1.90	0.03	99.6	0.005	-
Mo	0.25	-	-	99.8	-
Carbon	0.15*	0.01	0.10	0.01	Bal
Oxygen	0.20	0.08	0.125	0.150	-

* Additional graphite added to get 4640 composition.

TABLE 15-A

Mechanical Properties of Sintered Atomized and Mixed Elemental 4640 Powder

Powder Origin	Compacting Pressure tsi	Sintered Density g/cc	Ultimate Tensile Strength ksi	Yield Strength 0.2% Offset ksi	Tensile Elongation %	Transverse Rupture Strength ksi	Hardness R_b	Combined Carbon Content %
Sintered 2050°F 30 min/Dissociated Ammonia								
Atomized	26.6	6.51	—	A	—	77.8	50.6	0.35
	40.7	6.91	62.6	45.5	2.0	110.9	66.3	0.34
	60.0	7.21	—	B	—	138.0	77.4	0.35
Mixed Elemental	20.0	6.48	33.1	19.7	4.0	67.6	32.1	0.34
	30.0	6.87	52.4	31.3	6.0	95.0	46.5	0.34
	42.5	7.15	58.8	33.2	7.0	122.7	60.4	0.35
Sintered 2400°F/60 min/Dissociated Ammonia								
Atomized	26.6	6.59	—	A	—	96.7	55.2	0.34
	40.7	6.97	64.8	54.1	2.0	132.3	70.1	0.34
	60.0	7.28	—	B	—	165.9	78.3	0.35
Mixed Elemental	20.0	6.58	44.7	31.0	6.0	91.8	44.6	0.34
	30.0	6.98	54.5	40.4	6.0	119.6	21.8	0.32
	42.5	7.22	70.8	44.5	7.0	149.9	72.5	0.38

A - Green strength of these atomized bars too low to permit adequate handling and sintering.

B - Excessive lamination occurred in the atomized bars at this compacting pressure.

TABLE 16-A

Heat-Treated Properties
of Atomized and Mixed Elemental
4640 Steel Powders

Sintered: 2050°F/30 min/Dissociated Ammonia
Heat Treated: 1550°F/1 hr/Oil Quenched
+ Tempered 1 hr/Air Cooled

Atomized Powder			
Density, g/cc	6.50	6.91	7.20
Tempering Temperature, °F	600	600	500
Ultimate Tensile Strength, ksi	A	64.1	C
Yield Strength (0.2% Offset), ksi	A	B	C
Tensile Elongation, %	A	Nil	C
Transverse Rupture Strength, ksi	85.7	127.5	180.0
Hardness, R_B	88.3	98.3	106.7
Combined Carbon Content, %	0.38	0.37	0.40
Mixed Elemental Powder			
Density, g/cc	6.48	6.87	7.15
Tempering Temperature, °F	600	600	500
Ultimate Tensile Strength, ksi	73.4	101.1	143.6
Yield Strength (0.2% Offset), ksi	67.6	88.1	119.5
Tensile Elongation, %	1.0	1.5	1.0
Transverse Rupture Strength, ksi	124.1	176.4	239.5
Hardness, R_B	80.2	91.7	101.2
Combined Carbon Content, %	0.38	0.37	0.40

A - Green strength of these atomized bars too low to permit adequate handling and sintering.

B - Bars broke before 0.2% offset.

C - Excessive lamination occurred in atomized bars.

TABLE 17-A

Heat-Treated Properties
of Atomized and Mixed Elemental
4640 Steel Powders

Sintered: 2400°F/60 min/Dissociated Ammonia
Heat Treated: 1550°F/1 hr/Oil Quenched
+ Tempered 1 hr/Air Cooled

Atomized Powder			
Density, g/cc	6.59	6.97	7.27
Tempering Temperature, °F	600	600	400
Ultimate Tensile Strength, ksi	A	92.0	C
Yield Strength (0.2% Offset), ksi	A	B	C
Tensile Elongation, %	A	Nil	C
Transverse Rupture Strength, ksi	107.2	153.9	219.3
Hardness, R_B	91.7	99.7	109.0
Combined Carbon Content, %	0.38	0.39	0.38
Mixed Elemental Powder			
Density, g/cc	6.59	6.95	7.23
Tempering Temperature, °F	600	500	400
Ultimate Tensile Strength, ksi	96.1	145.5	186.7
Yield Strength (0.2% Offset), ksi	85.7	127.4	155.6
Tensile Elongation, %	1.0	1.0	1.0
Transverse Rupture Strength, ksi	176.5	252.5	317.1
Hardness, R_B	90.5	100.0	108.3
Combined Carbon Content, %	0.38	0.39	0.38

A - Green strength of these atomized bars too low to permit adequate handling and sintering.

B - Bars broke before 0.2% offset.

C - Excessive lamination occurred in atomized bars.

7. Data Group G

Reference: 24

Materials

Data is presented on the following steel compositions: 1040, 4640, 4665, and 1.35 Mn, 0.58 C. The material characteristics are given in Table 18-A.

Processing Summary

The powder blends were compacted into square bars approximately 0.44 × 0.44 × 3.0 in. long. The density of the compacts was 6.5 - 6.7 gm/cm^3. The compacting pressure used depended on the powder blend, but was approximately 80 ksi. The preforms were then preburned at 1200°F, sintered at 2000°F for 15 min in hydrogen, removed from the furnace and "hot forged" within 5 sec, and allowed to cool in air. The resulting samples were 97% minimum density.

Group G Data

Tensile properties of 1040 steel are presented in Table 19-A. Properties of as-forged 4640 and 4665 materials are given in Table 20-A. Some tensile properties of heat-treated primary and prealloyed 4665 and 1.35 Mn, 0.58 C steels are presented in Tables 21-A, 22-A and 23-A, respectively.

TABLE 18-A

Composition of Steels

Type	Alloy Element, wt% Ni	Mn	Mo	C
SAE 4640	1.85	0.7	0.25	0.40
Prealloyed 4600				
A. O. Smith	2.00	0.2	0.5	Added
Hoeganaes	1.85	0.2	0.5	Added
1.35 Mn, 0.58 C	-	1.35	-	0.58

Elemental Powders

Iron Powder	A. O. Smith E P 300 (Atomized)
Graphite	Southwestern Graphite #1651
Molybdenum	Fansteel P/M - 200 mesh
Nickel	International Nickel type 123
Zinc Stearate	Nopco P M G

TABLE 19-A

1040 Carbon Steel
Primary Blend

	Sintered Only	Hot Forged
Density, g/cc	6.60	7.67
Tensile Strength, psi	24,200	74,000
Yield Strength, psi	17,700	51,100
Elongation, % in 1 in.	1.8	25
Oil Quench from 1550°F and tempered at 350°F, 1 hr		
Tensile Strength, psi	44,800	107,000
Yield Strength, psi	38,000	72,000
Elongation, % in 1 in.	0.8	10

TABLE 20-A

Effect of Alloying Elements on Hot Forged Properties

Carbon Content	Tensile Strength psi	Yield Strength psi	Elongation % in 1 in.	Hardness Rockwell
0.40 - 0.45 Carbon				
1040 Forged	74,000	51,000	25	B-60
Primary 4600 (No Mo)	91,000	44,000	23	B-78
Primary 4600 (0.5 Mo)	96,000	52,000	20	B-82
Prealloyed	107,000	80,000	8	B-90
0.65 - 0.70 Carbon				
Primary 4600 (No Mo)	114,000	56,000	15	B-89
Primary 4600 (0.5 Mo)	125,000	61,000	14	B-92
Prealloyed	144,000	102,000	5	B-96

NOTE: Forged Densities -- 7.65 g/cc

TABLE 21-A

Properties of Primary 4665

Type	UTS, psi	YS, psi	El, %	Density, gm/cm^3
Sintered:				
4665, No Mo	47,300	28,800	2.4	6.8
As Forged:				
4665, No Mo	114,000	56,000	15	7.65
4665, 0.5 Mo	125,000	61,000	14	7.65
Heat Treated:				
4665, No Mo				
Tempered 350°F	285,000	185,000	1.5	
500°F	275,000	221,000	2.6	
650°F	212,000	178,000	5.1	
800°F	189,000	162,000	7.8	
4665, 0.5 Mo				
Tempered 350°F	276,000	215,000	1.0	
500°F	282,000	229,000	2.2	
650°F	220,000	192,000	4.5	
800°F	208,000	180,000	5.0	

TABLE 22-A

Properties of Prealloyed 4665

Temperature, °F	UTS, psi	YS, psi	El, %
350	283,000	239,000	0.7
500	290,000	250,000	1.3
650	242,000	220,000	2.1
800	213,000	145,000	4.3

TABLE 23-A

Properties of Prealloyed Manganese Steel

1.35 Mn 0.58 Carbon

	Tensile Strength psi	Yield Strength psi	Elongation % in 1 in.	Hardness Rockwell
As Forged	135,000	78,000	6.5	C-18
Tempering Temperature				
500°F	272,000	252,000	0.4	C-45
650°F	238,000	216,000	0.75	C-42
800°F	216,000	198,000	1.7	C-36
1000°F	147,000	136,000	6.0	C-34

8. Data Group H

Reference: 18

Materials

- AISI 460C + 0.25% C
  4600 + 0.35% C
  4600 + 0.5% C
- Carbon steels ranging from 0 to 0.5% C

Processing Summary

Preforms were protected from oxidation/decarburization by graphite coating or by an endothermic gas atmosphere. The other processing details which are available accompany the data tables.

Group H Data

The mechanical properties of normalized and carburized 4600 + 0.25 C steel are listed in Table 24A. Data for heat-treated 4600 + graphite are given in Table 25-A. Mechanical properties of some forged mild and carbon steels are shown in Table 26-A. Mechanical properties of steels using raw powders manufactured by different methods are presented in Table 27-A. Notes on fatigue resistance follow Table 27-A.

TABLE 24-A

Mechanical Properties of AISI 4600 + 0.25% Added Graphite

Treatment	UTS, ksi	Elongation, %	R.A., %	Hardness, Case	HV 30 Core
Normalized	67.6	15	25	-	150/150
Carburized and Oil-Quenched*	115.8	10	20	750/772	260/264

* Material gas-carburized 2 hr at 1688°F; oil-quenched direct.
Subzero treatment 1 1/2 hr at -22°F.
Total case depth: 0.032 in.
Effective case depth: 0.028 in.

TABLE 25-A

Mechanical Properties of Heat-Treated AISI 4600 + Graphite

Added Graphite, %	Final C %	Austenitizing Temperature, °F	Temper. °F	UTS ksi	Elong. %	R.A. %	HV 30
0.25	0.24	1688	-22	116.2	12	25	200
0.35	0.32	1580	1220	95.0	23	38	240/250
			1157	123.2	12	20	300/320
0.50	0.45	1562	1022	147.0	12	20	353

TABLE 26-A

Mechanical Properties
of Some Forged Mild and Carbon Steels

Starting material: 0.02% C, 0.03% Mn, 0.018 Si, 0.12% P

Added Graphite	Final C %	UTS, ksi	Elastic Limit, ksi	Elongation %	R.A. %
0	0.02	49.6	-	28	43
0.5	0.12	54.4	46.4	33	62
1.0	0.44	86.4	53.2	21	35
En-2 wrought, 0.4 Mn	0.13	52.0	36.0	40	67

TABLE 27-A

Mechanical Properties of Mild and Carbon Steels
Using Powders Manufactured by Different Methods

Material Origin	Final C %	UTS, ksi	Elastic Limit, ksi	Elongation %	R.A. %
Electrolytic iron	0.04	44.4	38.4	46.4	76.5
	0.37	69.2	43.8	31.0	52.3
Water-atomized iron	0.017	50.2	40.0	39.5	69.5
	0.460	82.6	48.0	20.3	35.3
Air-Atomized iron	0.020	49.0	-	29.0	45
	0.440	86.4	-	21.0	35
Wrought Steel	0.03	40	23.0	43	
	0.40	85.0	60.0	21	

Note the good approximation of P/M products to wrought materials in the case of the Fe-C alloys listed in the preceding table.

Notes on Fatigue Testing

Bending fatigue curves of powder-forged and wrought Mn-Mo and AISI 4632 connecting rods were determined. The wrought material exhibited somewhat better fatigue properties in all cases. The fatigue strength curves tend to converge with increasing cycles, however, attaining similar values at 10^7 cycles. GKN endurance test programs have shown powder-forged rods to be comparable to their wrought counterparts.

9. Data Group I

Reference: 3

Materials

A wide range of steel compositions was investigated, including unalloyed irons, EN 18A, SAE 8600 + C, SAE 4600 + C, and Fe-C, Fe-Ni-C, Fe-Ni-Mo-C, Fe-Cr-C, and Fe-Cr-Ni-C alloys. Both blended and atomized alloys were studied. The material properties are given in Tables 28-A and 29-A.

Processing Summary

- The forging method used throughout is "sinter-forging" (synonymous with hot repressing, hot densification, hot coining, or hot restriking).
- All samples were initially compacted at 50 ksi, in a 2.30 in. diameter die. Sintering was done in a hydrogen atmosphere generally at 2102°F. Atomized alloys were sintered for 1/2 hr, blended alloys for 1 hr.
- Preforms were preheated prior to forging in an inert atmosphere in the range 1830°F - 2010°F. By the start of pressing the temperature of the samples had fallen to 1740°F - 1830°F. The hot pressing die was 2.38 in. in diameter. The hot pressing pressure was 50 ksi.
- Low carbon samples were generally given a normalizing treatment of air cooling from 1650°F. Samples containing >0.2% C were heat treated by oil quenching from temperatures in the range 1530°F - 1650°F, followed by tempering at 570°F or 1112°F.

Group I Data

- Examples of densities obtained at different stages of the processing are shown in Table 30-A.
- Mechanical properties of normalized sinter/forged iron and iron-carbon samples are shown in Table 31-A.
- Tensile properties of sinter/forged blended alloys of Fe-Ni-C, Fe-Ni-Mo-C, Fe-Cr-C and Fe-Cr-Ni-C are shown in Table 32-A.

- Mechanical properties of sinter/forged samples made from atomized En 18A and SAE 8600 powders are shown in Table 33-A.
- Mechanical properties of sinter/forged SAE 4600 alloys, both normalized and heat treated, are given in Table 34-A.
- The effect of different sintering treatments on the mechanical properties of blended and atomized alloys is shown in Table 35-A.
- The effect of different iron powders on the mechanical properties of a blended alloy of nominal composition 2% Ni, 0.5% Mo, 0.5% C is shown in Table 36-A.

TABLE 28-A

Iron Powder Characteristics

Powder	Manufacturing Process	Grade	Apparent Density, g/cm^3	Compressibility,* g/cm^3	Flow Rate, s/50 g
A	Chloride reduction	Normal - 100 mesh	2.44	6.21	34
B	Chloride reduction	High compressibility	2.96	6.40	27
C	Oxide reduction	Normal - 100 mesh	2.39	6.49	32
D	Oxide reduction	High compressibility	2.54	6.30	32
E	Oxide reduction	High compressibility	2.68	6.45	29
F	Water atomization	Normal - 100 mesh	2.96	6.44	35
G	Electrolysis	-300 mesh	2.49	6.40	-
H	Oxide reduction	-300 mesh	2.49	6.17	-

* 50 ksi; no lubricant

TABLE 29-A

Composition and Properties of Water-Atomized Alloy Powders

	Composition, wt%										
Powder	C	Si	Mn	S	P	Ni	Cr	Mo	Apparent Density, g/cm^3	Compressibility,* g/cm^3	Flow Rate, s/50 g
En 18A	0.26	0 32	0.75	0.02	0.01	0.24	1.2	-	2.84	5.30	33
SAE 8600	0.01	0.02	0.09	0.012	0.007	0.59	0.60	0.49	3.33	6.14	23
SAE 4600	0.01	0.03	0.12	0.015	0.008	1.70	-	0.42	3.08	6.30	25

* 50 ksi; no lubricant.

TABLE 30-A

Densities of Iron and Alloy Samples at Various Stages in Processing, gm/cm^3

Powder/Alloy	Pressed	Sintered	Hot-Pressed	Calculated Absolute Density
A	6.21	6.25	7.82	7.835
C	6.19	6.25	7.76	7.80
D	6.30	6.32	7.79	7.83
F	6.44	6.53	7.84	7.855
G	6.40	6.41	7.85	7.865
SAE 4600	6.30	6.34	7.85	7.875
SAE 4600 + 1/2% C	6.30	6.35	7.83	7.870
EN 18A + 0.3% C	5.30	5.70	7.75	7.775
SAE 8600	6.14	6.16	7.77	7.825
SAE 8600 + 1/2% C	6.15	6.17	7.81	7.845

TABLE 31-A

Mechanical Properties of Sinter/Forged Iron and Iron-Carbon Samples

(Samples with 0.5% C added were normalized from 1562°F, other samples from 1652°F)

Powder	Carbon Added, %	Yield Stress, ksi	UTS, ksi	Elongation, %	Reduction in Area, %	Charpy Impact Value, ft-lb
A	0	32	42	25	40	26
C	0	30	42	29	35	14
C	0.5	42	58	19	22	3
D	0	28	43	25	47	14
D	0.5	40	58	20	28	3
F	0	38	48	38	71	22
F	0.25	40	56	30	57	10.5
F	0.5	60	80	22	51	10.5
G	0	28	43	43	79	19
G	0.5	23	64	24	45	2.5

TABLE 32-A

Tensile Properties of Sinter/Forged Blended Alloys made from Chloride-Reduced Iron (Powder A)

Nominal Composition wt%	Tempering Temp., °F	Yield Strength, ksi	UTS, ksi	Elongation, %	R.A., %	HV
1 1/4% Ni, 1/4% C	572	52	76	15	28	182
	1112	-	68	24	45	146
1 1/4% Ni, 1/2% C	572	64	94	18	38	277
	1112	-	88	20	49	198
1 1/4% Ni, 0.8% C	572	94	136	9	25	342
	1112	94	118	12	38	279
2% Ni, 1/2% Mo, 1/4% C	572	52	80	16	32	171
	1112	-	72	22.5	40	160
2% Ni, 1/2% Mo, 1/2% C	572	66	110	5	7.5	279
	1112	-	96	16	35	249
2% Ni, 1/2% Mo, 0.8% C	572	106	144	9	20	330
	1112	74	116	13	28	255
1 1/4% Cr, 1/2% C	572	-	126	4	11	306
	1112	-	86	14	26	237
1 1/4% Cr, 1/2% Ni, 1/2% C	572	64	124	6	10	292
	1112	-	90	10	17	222
1 1/4% Cr, 1/2% Ni, 0.8% C	572	84	134	5	4	330
	1112	76	110	10	12	274

TABLE 33-A

Mechanical Properties of Sinter/Forged Samples made from Atomized En 18A and SAE 8600 Powders

(All samples oil-quenched and tempered as indicated)

Powder	Nominal % Carbon	Tempering Temp., °F	0.2% Yield Stress, ksi	UTS, ksi	Elongation %	R.A., %	Charpy Impact Value, ft-lb
En 18A	0.26	572	64	92	6	7	-
		1112	60	82	6	6	-
En 18A	0.56	572	100	134	4.5	6	-
		1112	80	96	12.5	26	3
En 18A	0.76	572	148	160 (unbroken)			-
		1112	92	110	15	29	-
SAE 8600	0	1112	46*	56	10	10	8
SAE 8600	0.25	1112	50	70	14	19	7
SAE 8600	0.375	1112	68*	84	10	16	4
SAE 8600	0.5	1112	78*	96	11	20	6

* Upper yield point.

TABLE 34-A

Mechanical Properties of Sinter/Forged SAE 4600 Alloys

% Carbon Added	Heat Treatment*	0.2% Yield Stress, ksi	UTS, ksi	Elongation, %	R.A., %
0	AC	-	54	48	74
0.1	AC	-	55	45.5	68
0.125	AC	-	60	30	55
0.2	AC	-	68	20	27
0.3	AC	-	75	21	55
0.325	AC	53	76	22	51
0.4	AC	62	90	19.5	51
0.5	AC	66	93	16	47
0.6	AC	66	96	14.5	32
0	1112	-	60	31	68
0.1	1112	-	71	25	69
0.2	1112	73	88	20	57
0.25	572	76	94	18	46
0.25	1112	74	92	20	60
0.4	572	101	136	9	35
0.4	1112	76	100	17.5	47
0.5	752	164	180	10	38
0.5	1112	82	111	18	54
0.6	572	211	276	3.5	3
0.6	752	177	199	5	10
0.6	1112	120	144	5.5	15

* AC - Air-cooled (normalized).

T572 - Oil quenched and tempered at 572°F, etc.

TABLE 35-A

Effect of Different Sintering Treatments on the Tensile and Impact Properties of Blended and Atomized Alloys

(All samples oil quenched, tempered at 1112°F)

Alloy	Temp., °F	Sintering time, hr	0.2% Yield Stress, ksi	UTS, ksi	Elongation %	R.A., %	Charpy Impact Value ft-lb
Powder A + 2 1/2% Ni, 1/2% Mo, 1/4% C	2100	0.5	-	66	26	47	27.5
	2100	1	-	70	25	47	28
	2370	1	-	73	22	35	26.5
	2370	2	-	83	19	30	29.5
SAE 4600 + 1/2% C	2100	0.5	74	108	15	45	8
	2370	1	82	115	15	49	11.5
	2370	2	82	110	19	58	13.5

TABLE 36-A

Effect of Different Iron Powders on the Mechanical Properties of a Blended Alloy of Nominal Composition 2% Ni, 0.5% Mo, 0.5% C

(All samples were sintered at 2370°F, then oil-quenched and tempered at 1112°F)

Powder	Type	UTS, ksi	Elongation, %	R.A., %	Charpy Impact Value ft-lb	Oxygen Content, wt%
A	Chloride reduction	96	16	35	11.5	0.14
B	Chloride reduction HC*	90	15	41	14.5	0.036
C	Reduced Iron	91	10	17	8	0.32
D	Reduced Iron HC	80	15	22	10.5	0.24
E	Reduced Iron HC	84	13.5	24	9	0.24
F	Atomized Iron	94	16	38	13	0.032
G	Electrolytic (-300 mesh)	103	14	30	13.5	0.09
H	Reduced Iron (-300 mesh)	77	16	23	9.5	0.34

* HC - High compressibility.

Other Sources of Information

There are a number of other extensive sources of information available on ferrous P/M products which have not been incorporated into the present data compilation, either because the subject matter was not considered strictly relevant (e.g., data presentations concerned with only sintered material, or only nonheat-treatable material, would generally not be included), because the processing, test, or sample data are not presented in sufficiently specific detail, or because inclusion of the data in this compilation was considered to be unnecessary duplication of readily available sources. Data sources which are particularly useful in that they present a broad spectrum of P/M material properties in a reasonably condensed form are referenced below.

1. "P/M Materials Standards and Specifications," MPIF Standard No. 35, published by Metal Powder Industries Federation, 201 East 42nd St., New York, N.Y., 10017, copyright 1969.

   This work contains a large quantity of mechanical property data on nickel-steel P/M products, heat treated and otherwise, arranged as a function of composition (range) and density (range). In addition, data on brasses, bronzes, Fe-Cu alloys, carbon steels, infiltrated steels, and stainless steels are presented.

2. "Properties and Applications of Powder Metallurgy Parts," data sheets compiled by S. W. McGee, Burgess-Norton Mfg. Co., reported in Metal Progress, April 1971, pp. 80-81.

3. ASTM Standard Specifications.

- ASTM B310: Standard Specification for Sintered Carbon-Steel Structural Parts.

  The typical mechanical properties which can be expected from as-sintered and heat-treated carbon-steel P/M specimens as a function of carbon content and density.

- ASTM B426: Standard Specification for Sintered Copper-Steel Structural Parts.

  The typical mechanical properties which can be expected from as-sintered and heat treated carbon steel P/M specimens as a function of amount of copper added and specimen density.

- ASTM B308: Standard Specification for Sintered Carbon-Steel Structural Parts.

  The tensile and compressive properties which can be expected from sintered iron infiltrated parts are presented as a function of combined carbon.

- ASTM B484: Standard Specification for Sintered Nickel-Steel Structural Parts.

  The mechanical properties which can be expected from as-sintered and heat-treated nickel specimens are presented as a function of nickel, combined carbon, and density.